DTU Library

Modelling architectures in multi-product oriented technology development

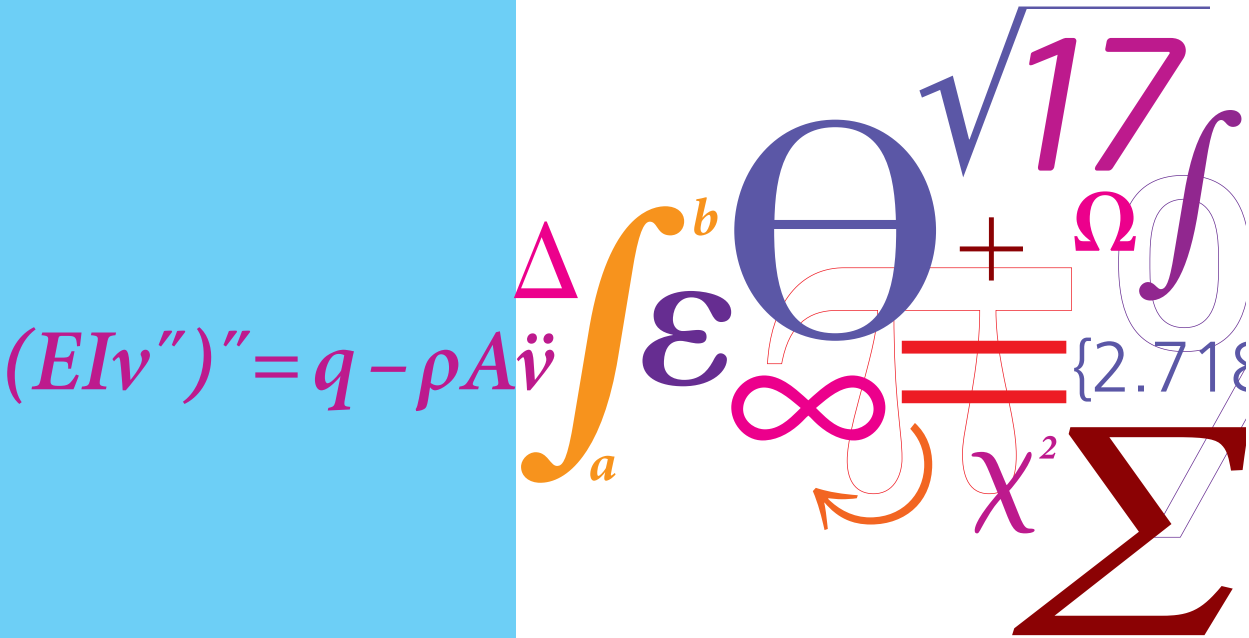
Guðlaugsson, Tómas Vignir

Publication date:
2015

Document Version
Publisher's PDF, also known as Version of record

Modelling architectures in multi-product oriented technology development

PhD Thesis



Tómas Vignir Guðlaugsson
DCAMM Special Report No. S192
July 2015

DTU Mechanical Engineering
Department of Mechanical Engineering

Technical University of Denmark

Tómas Vignir Guðlaugsson

Modelling architectures in multi-product oriented technology development

PhD Thesis, July 2015

DTU Mechanical Engineering
Department of Mechanical Engineering

Guðlaugsson, T.V. (2015). *Modelling architectures in multi-product oriented technology development*. PhD Thesis, Technical University of Denmark.

This report was prepared by

Tómas Vignir Guðlaugsson

Supervisors

Main supervisor
Niels Henrik Mortensen
Professor, PhD, Head of section
Section of Engineering Design and Product Development
Department of Mechanical Engineering
Technical University of Denmark

Co-supervisor
Lars Hvam
Professor, PhD
Section of Operations Management
Department of Management Engineering
Technical University of Denmark

Opponents

Torben Lenau
Associate Professor, PhD
Section of Engineering Design and Product Development
Department of Mechanical Engineering
Technical University of Denmark

Hans Petter Hildre
Dean, Professor, PhD
Marine Technology and Operations
Aalesund University College

Antti Pulkkinen
University Lecturer, Dr. Tech.
Mechanical Engineering and Industrial Systems
Tampere University of Technology

Release date:	30th July 2015
Category:	1 (public)
Edition:	Final
Comments:	This thesis is submitted in partial fulfillment of the requirements for obtaining the PhD degree at the Technical University of Denmark.

DTU Mechanical Engineering
Section of Engineering Design and Product Development
Technical University of Denmark
Produktionstorvet bygning 426
DK-2800 Kgs. Lyngby
Denmark

www.mek.dtu.dk/Sektioner/KP
Tel: (+45) 45 25 19 60
info@mek.dtu.dk
phd@mek.dtu.dk
ISBN: 978-87-7475-437-4

Abstract

This thesis investigates the use of architecture modelling in a technology development context. This context presents greater uncertainties than more mature new product development. Applications—the use of products based on the technology being developed—are not fully identified and the requirements to be fulfilled are not completely defined. The products to be based on the technology are yet to be developed as the foundation for their development will be developed during the technology development. Furthermore, the production of a new technology is not defined as both the technology and derivative products are not completely defined. Yet, decisions need to be made during technology development on the capabilities to be provided through the development to fulfil future application requirements, provide a foundation for future products, and development of a production system capable of producing future products and supporting technology development through prototype production.

To support technology development aimed at a broad range of application requirements, two modelling frameworks are introduced: the *product technology architecture modelling framework* and the *production architecture modelling framework*—both developed for implementation within a technology development context. Both frameworks model both structural aspects and functional aspects of their respective phenomena.

The *Product Technology Architecture modelling framework* enables modelling a product technology architecture including the structure and breakdown of product technologies based on a generic product technology architecture as organs and organ alternatives and links these through product concepts to application concepts and requirements.

The *Production Architecture modelling framework* enables modelling a Production Architecture from three perspectives: structure, capabilities, and expansions. These perspectives provide the means to model what the Production Architecture *is*, what the Production Architecture *does*, and what the Production Architecture has the *potential to do* within the planning horizon.

The results of implementing the modelling frameworks in a technology development project are presented, along with descriptive results on the context of technology development gained through active participation in the case project.

Keywords: Architecture modelling – Product technology architecture – Product architecture – Production architecture – Technology development – Technology platforms

Resumé

Denne afhandling undersøger brugen af arkitekturmodellering i en teknologiudviklingskontekst. Denne kontekst præsenterer større usikkerheder end er tilfældet i mere konventionel produktudvikling. Applikationer—hvor produkter som vil blive udviklet på basis af teknologien der er under udvikling—er ikke fuldt identificeret og de krav der skal opfyldes er ikke fuldt definerede. Produkterne der skal baseres på teknologien er ikke udviklet endnu, da deres fundament vil blive udviklet igennem teknologiudviklings-forløbet. Endvidere er produktionen af en ny teknologi ikke fuldt defineret, da hverken teknologien eller produkter baseret på teknologien, er blevet fuldt defineret. Men beslutninger skal træffes alligevel, som en del af teknologiudviklingsforløbet, omkring hvad skal opnås igennem teknologiudviklings-forløbet til at opfylde applikationskrav, igennem et fundament for fremtidige produkter, og i form af et produktionssystem i stand til at producere fremtidige produkter og støtte teknologiudviklingen ved produktion af prototyper.

Til at støtte teknologiudvikling, målrettet mod opfyldelse af en bred vifte af applikationskrav, er to modellerings-rammeværker introduceret: et rammeværk til modellering af produktteknologi-arkitektur og et rammeværk til at modellere produktionsarkitektur—hvor begge er blevet udviklet til at blive implementeret i en teknologiudviklings-kontekst. Begge rammeværker indeholder både strukturelle og funktionelle aspekter af de fænomener de modellerer.

Product Technology Architecture modellerings rammeværket faciliterer modellering af Produktteknologi-arkitektur, som indeholder dens struktur og en nedbrydning af produktteknologier, baseret på en generisk produktteknologi-arkitektur, i organer og organ-alternativer og modellerer deres relationer til applikationskoncepter og krav igennem produktkoncepter.

Production Architecture er et modellerings rammeværk der faciliterer modellering af en produktionsarkitektur fra tre perspektiver: dens struktur, dens evner i forhold til produktvarianter, samt dens planlagte udvidelser. Disse perspektiver gør det muligt at modellere hvad produktionsarkitekturen er, hvad den kan, og hvad den har potentiale til at kunne indenfor planlægningshorisonten.

Resultaterne af at implementere disse rammeværker i et teknologiudviklingsprojekt er præsenteret, sammen med deskriptive resultater omkring teknologiudviklingskonteksten, som stammer fra aktiv deltagelse i det industrielle projekt.

Stikord: Arkitektur-modellering – Produktteknologi-arkitektur – Produkt-arkitektur – Produktions-arkitektur – Teknologi-udvikling – Teknologi-platforme

Preface and Acknowledgment

This PhD Thesis is the documentation of a PhD project carried out at the Department of Mechanical Engineering at the Technical University of Denmark (DTU). The PhD project was initiated in November 2011 and ended in July 2015. The PhD project had a duration of 36 months but was interrupted by a leave of absence for two 5 month periods.

The PhD project was financed by Innovation Fund Denmark as part of the "ATF DEAP Actuator and Generator Project" (the DEAP project). Their support is gratefully acknowledged. The research was performed in close collaboration with especially Danfoss PolyPower A/S but also the other collaborating partners in the project.

This PhD thesis would not have been a written without the support of the many people that have provided support and insight throughout the project. I would like to express my gratitude to those who have been most influential.

My main supervisor Professor Niels Henrik Mortensen, who throughout the project has provided me with inspiration, critique, guidance, and flexibility to continue my work.

My co-supervisor Professor Lars Hvam who has provided both practical and theoretical advice at times when they were needed—they made a difference.

Professor Emeritus Mogens Myrup Andreasen has been willing to discuss my work, engineering design, and my thesis writing process on many occasions—which has been a great help.

The collaboration with partners from the DEAP project has been fruitful and given insight into the industrial domain. My close collaboration with Rahimullah Sarban has been a key element in my research. I am thankful for our numerous discussions on the development project—and unrelated subjects—and your support for the academic side of my work. Hans-Erik Kiil, Jens Juul Yde, and Ulrik Jørgensen have indulged me in numerous discussions providing me with both insight and critique, for which I am grateful. Benjamin, Kim, Rasmus, Chai, Alan, and Jakob—your willingness to participate and discuss my work and your honesty in your feedback has been valuable throughout the project.

I express my gratitude to the people of IPU, where I had an office for two years, for their hospitality and willingness to share insights from their vast experience with product development. During this time I was fortunate enough to work with Thorkild Ahm—who passed away during the course of the project—whom I will always remember for his support, hospitality, inspiration, and willingness to discuss my ideas.

The colleagues from the DEAP project who have yet to be mentioned; you have not been forgotten, but you are too numerous to be mentioned—I am however glad to have had the opportunity to work with such a competent and heterogeneous group of people. Perhaps some of us can have a reunion in San Diego sometime?

Professor Mitchell Tseng and his group at the Advanced Manufacturing Institute at Hong Kong University of Science and Technology are gratefully acknowledged for their hospitality during my all-too-brief visit.

To my colleagues in the section of engineering design and product development; it's been great working with you and discussing everything from engineering design to the best brewing methods for coffee—which are not entirely unrelated subjects. My fellow PhD students—both new and old—have played a central part of creating the positive and supportive work environment that I have enjoyed during my PhD project. Poul Martin Ravn has played a special role in these years through our collaboration in the DEAP project—a role which he has played with outstanding remarks, whether travelling by planes, trains, or auto-mobiles, discussing theory or practise, collaborating in our research, or taking a stroll to the shop.

Last but not least, I thank my wife Helga and my children—Aníta Rós and Óliver Vignir—who have felt my absence—in both physical and mental sense—at various times throughout the project, my parents for their belief in me, and my in-laws for their support and hours of proofreading.

Tómas Vignir Guðlaugsson
Kgs. Lyngby, July, 2015.

Contents

List of Figures

List of Tables

Abbreviations and definition of terms

DEAP Dielectric Electro-Active Polymer. 47, 48, **48**, 49–52, 55, 56, 65, 66, 68, 70–73, 75–77, 80–82, 84, 85, 92

DEAP project The central case project—A large project with multiple collaborators that worked together in work packages on developing various aspects of DEAP technology with the aim of providing the foundation for commercializing a DEAP technology based transducer platform. 18, 19, 47, 48, 50, 51, 53–57, 59, 61, 62, 64, 66–68, 75, 77, 79, 80, 82, 83, 86, 87, 89, 90, 92, 95–100, 103

DEAP transducer A transducer constructed using DEAP technology. A DEAP transducer may be used for sensing, actuation, or energy generation applications. 20, 49–53, 64–66, 68, 76, 92, 94

DEAP transducer platform The goal of the DEAP project was to develop the foundation of a DEAP transducer platform—product platform—defining standard designs for DEAP transducers capable of fulfilling a wide range of application requirements while enabling reuse of parts and functional principles. 51

DS-I Descriptive Study I—part of Design Research Methodology framework. 14, 18, 19, *see also* Design Research Methodology

DS-II Descriptive Study II—part of Design Research Methodology framework. 14, 17, 19, 20, *see also* Design Research Methodology

EAP Electro-Active Polymer—an alternative term for DEAP that covers a wider classification than DEAP. Was mainly used in publications. Internally in the research project, the term DEAP was primarily used. 69, *see also* DEAP

NPD New Product Development. 3–5, 7, 9, 28, 45, 61, 63, 68, 76, 87, 100, 102

PS Prescriptive Study—part of Design Research Methodology framework. 14, 17, 19, *see also* Design Research Methodology

RC Research Clarification—part of Design Research Methodology framework. 14, 19, *see also* Design Research Methodology

DNATF Danish National Advanced Technology Foundation—predecessor to Innovation Fund Denmark. 75, *see also* IFD

DSM Design Structure Matrix. 38, 39, 41, 42

IFD Innovation Fund Denmark—main funding organisation for the DEAP project. 47

PFMP Product Family Master Plan. 39–42, 46, 64, 71, 76

RQ Research Question. 8–10, 19, 59, 60, 69, 76–78, 82, 87, 89, 90, 92

DEAP Production Architecture The Production Architecture in the DEAP project. 82, 86, 87, 94, 96–98, *see also* DEAP & Production Architecture

Action Research A research methodology in which the researcher actively participates within the area of concern during the research. 13, 14, **14**, 15, **15**, 17, 18, 101

Conceptual Product Platform A modelling framework to model a product technology architecture during technology development. *see also* Product Technology Architecture

Danfoss PolyPower The firm developing DEAP technology and transducers. 48, 50, 56, 66, 72, 73, 75, 77, 96

Design Research Methodology A research methodology with a framework for stepwise and iteratively developing research based support within engineering design. 13, **13**, 14, 15, 17–19, 99, 101

Genetic Design Model System A framework defining a product model comprising four classes of models: constitutive/behavioural, soll / ist, core / view, and design / life phase. 13, **28**, 29, 30, 39, 45, 46

Product Technology A particular way in which natural phenomena can be utilized and arranged as a partial solution to how a system can achieve its intended purpose. 2, 3, 5–8, 13, 26, 34–36, 45, 46, 50–53, 56, 64–68, 70, 71, 77, 90, 92, 93, 97, 102, 103

Product Technology Architecture A purposefully aligned description of the structure, relations, and purpose of product technologies from which a group of related products can be developed. 6, 9, 33, 39, 45, 46, 51, 63–65, 67, 68, 70, 71, 73–77, 90, 92–94, 96, 97, 102–104

Production Architecture A modelling framework for the modelling of the architecture of a production system during development in support of identification and communication of capabilities and decision making regarding expansions to the production system. 9, 10, 42–44, 46, 55, 79–87, 94–98, 102, 103

Technology Prototype A type of prototype developed to investigate and demonstrate the performance of a novel technology. 51, 53, 60, 61, 63, 66–68, 90, 91

Technology Prototype Product Architecture Tool An architecture modelling tool developed to support the development of technology prototypes. 63, 67, 68, *see also* Technology Prototype

Technology Readiness Level An approach to assess the maturity of a technology in terms of how close it is to being ready for deployment in an actual system in the intended environment. 2, 3, 23, 24, 36, 53, 94

Theory of Domains A design theory that defines three domains—viewpoints—of a technical artefact to be taken into consideration during development: Activity domain, Organ domain, and Part domain. 13, 26, **26**, 27, 45, 101, 102

Theory of Technical Systems A comprehensive theory aimed at providing a perspective from which all technical systems can be seen and understood. 1, 7, 13, 25, **25**, 26, 45

Work Package The DEAP project was divided into sub-projects that were denoted as Work Packages—each with their own goals and resources—which in combination and collaboration aimed at reaching the DEAP project goals. 18, 19, 48, **48**, 50–53, 55–57, 59, 61–68, 75, 77, 81, 86, 93, 94, 98

CHAPTER 1

Introduction

'Begin at the beginning,' the King said, very gravely, 'and go on till you come to the end: then stop.'

—Lewis Carrol, *Alice's adventures in Wonderland* (1865)

The introduction describes the background for this research and the problem area. The scope of this thesis is described in section 1.2. The research objectives are described in section 1.3. This includes a presentation of the Research Questions guiding this research.

1.1 Background

The development and utilization of new technologies sets humans apart from other species (Aunger, 2010). Technology has so greatly influenced mankind throughout history that the diffusion of new technologies is what defines many periods of human history—from the stone age to the industrial age.

Technology has been defined in various ways in literature Aunger (2010); Schatzberg (2006); Thenent et al. (2012). Some consider the word limited to know-how related to production processes—production technology. Others consider it a much broader term covering a much broader concept, e.g.:

> A technology is a phenomenon captured and put to use. Or more accurately I should say it is a *collection* of phenomena captured and put to use.
>
> *(Arthur, 2009, p. 51)*

While limiting *technology* to production technology seems to this author to be too limited in scope to capture the elements of technology development, the latter definition does not—on its own—provide an operational definition of the term. However, it captures elements inherent to technology development: during technology development, a phenomenon needs to be both captured and put to use. Finally, in Theory of Technical Systems, technology is seen as "the specific way of delivering an effect to an operand"(Hubka and Eder, 1988, p. 260), encompassing the "knowledge about the transformation" that "formulates what effects are needed" (Eder, 1998, p. 362).

Mankins (1995) described Technology Readiness Levels on the basis of how far the development has reached on its path from identifying and describing a phenomena with a potential use, predicting and reaching performance levels within an intended use, towards implementing a fully developed physical instance of a system that utilizes the phenomena in an actual application environment.

Technology development in industry—after a potentially useful phenomena has been identified—can be seen as concerned with the clarification of three perspectives:

Product Technology How can the physical (and potentially non-physical if the definition is broad enough) elements of a system be arranged in such a way that the captured phenomena can be put to use?

Production technology How can physical inputs be transformed into the elements of the system enabling the use of the technology?

Use technology How and where can the phenomena be put to use within society?

While the first two perspectives deal directly with enabling the utilization of the phenomenon—the technology—the last perspective deals with the *what for* of technology development: what should the phenomenon be used for? As illustrated in figure 1.1, this perspective is both dependent on the two first perspectives—for a phenomenon to be utilized it must be captured in a system and this system must be produced—and it provides the frame of use that defines what the two prior perspectives should aim to achieve. The dependencies exist through the product as an intermediary—e.g. realising Product Technologies in the product, using the product, and experiencing the quality of the product. Furthermore—as illustrated in figure 1.1—each perspective contains stakeholders and activities that affect the outcome of the technology development.

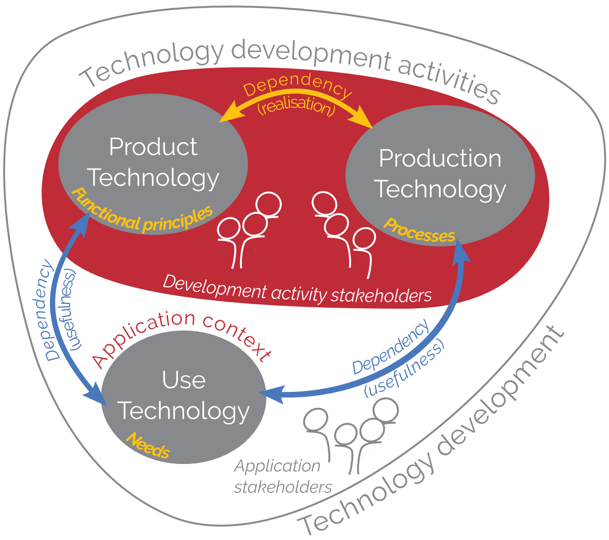


Figure 1.1: Each element of a technology's development is interlinked with other elements and exists within the context of the technology's development.

Technology development differs from more mature product development in a number of factors. Eldred and McGrath (1997) listed contrasting characteristics of technology and product development, which are gathered in table 1.1.

Table 1.1: Differences in key characteristics of technology versus product development (Characteristics taken from Eldred and McGrath (1997, page unknown))

Technology development	Product development
Project cycle times are usually difficult to estimate	Project cycle times can be accurately estimated
Too much structure can inhibit creativity	Creativity is less of an issue, while structure and discipline are critical
It is difficult to capture process experience and leverage it for future technology development efforts	Repeatable processes and tasks allow leverage from premier experience
Because experimental outcomes are not known, highly detailed overall project plans are not practical	Project planning and management skills and structure are required
Depending upon the technology, the degree of confidence or level of understanding prior to entering product development can be highly subjective and hence cause communication problems	
Project leaders must be able to manage uncertainty while focusing on project goals	

Technology development in an industrial context provides a foundation for new products and a competitive advantage for the firms able to utilize its results (Walsh, 2004). New technology development generally carries more risks and unknowns than more mature product development, but is vital for the long-term prosperity of the firm (Cooper, 2006).

However, it is not always clear where the advantage of a new technology will be the greatest, when it is first being presented to the market. In order to ensure competitiveness, leverage development costs and production system investments, and deal with increasing variety in market demands, firms have increasingly adopted platform based development (Pirmoradi et al., 2014). Platform based development enables firms to derive product variants from a common set of components or assets. Platform based development must be performed on the basis of a broad set of requirements fitting to the markets that the resulting product families are meant to be introduced in. Technology development within firms adopting a platform based development strategy must take a similarly broad perspective if the technology developed is to be implemented in a broad product portfolio.

Technology development projects can take many forms. One such form is developing the foundation for a set of new products and processes. Here, high degree of technology novelty leads to greater task uncertainty than in projects with a lower degree of technology novelty and greater time-to-market uncertainties - particularly when production process technology novelty is high (Tatikonda and Rosenthal, 2000). Mankins (1995) described nine Technology Readiness Levels of which levels three-to-five are often described as technology development stages, preceding New Product Development (NPD) (Berglund et al., 2008; Mankins, 2009). Figure 1.2 shows graphically how technology development—which includes development of use technologies, Product Technologies, and production technologies—precedes NPD, which in turn takes over when the maturity of the technology is high enough. Methods, tools, and approaches developed for use within a more mature technology environment do not always fit the greater uncertainties and lack of definition of the products and production system that is inherent in the early phases of development. However, while a plethora of

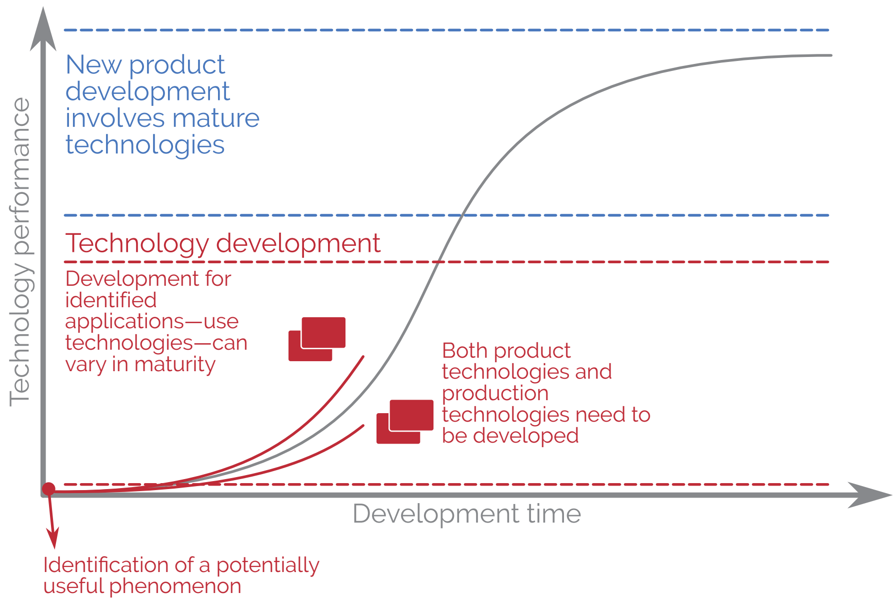


Figure 1.2: Technology development is performed within a low technology maturity environment. New Product Development involves more mature technologies.

tools and methods can be found for use within a NPD, few can be found to support the early phases of concurrent development of product and production system architectures. In these early phases, there are particular challenges that meet the stakeholders, e.g.:

- Although products may be envisioned, they have not been completely defined and may change drastically during the project
- The production system must be developed and can not be fully defined at project initiation
- While some applications for the products have been envisioned, there are great uncertainties regarding in what applications the technology will provide the greatest value (Rosenberg, 1996)
- The requirements of applications for a new functional principle are unknown and can only vaguely be estimated by looking at current technologies
- How much performance can be obtained through the development of the technology and product principles is unknown and must be determined through prototype testing
- The obtainable quality is unknown and must be determined through development of production processes
- The obtainable quality in industrial production quantities can only be reliably determined on industrial production equipment (Galagan et al., 2011)
- The development goal can be to develop the foundation for a whole range of different products

Despite these challenges, resources have to be allocated and decisions have to be made on how to proceed through the project.

Within NPD environments, the use of systematic approaches have been shown to support the design of new products and to collaborate across domains of expertise. The systematic design of both single products and product platforms has been supported by architecture modelling approaches in industrial cases (Harlou, 2006; Torry-Smith, 2013). But there are very limited sources within product platform development literature and engineering design literature that describe a systematic approach to and application of architecture modelling within technology development. Why is that? Technology platforms have been implemented in industry as a way to introduce commonality across wider application ranges than with product platforms and to provide a foundation for product platforms (Levandowski et al., 2012)—apparently, adopting a platform based approach on technology has been seen before. Why, then, have architecture modelling approaches not been described for use with technology platforms or in technology development?

While the application of traditional management techniques directly in projects with high technology novelty has been warned against, NPD approaches to development management have been adapted for use within a technology development environment and showed promising results (Cooper, 2006; Högman, 2011). As illustrated in figure 1.3, technology development carries greater risk and operational freedom than product development, but with less clarity of goals and requires lower strictness of methods (Aalto et al., 2003). If architecture modelling is to be implemented in technology development, the context and requirements for the modelling task may be different than for the analogous modelling task in NPD, as has been shown for management techniques. However, while NPD approaches may not be fit for direct implementation in an early phase, they may provide the foundation for new approaches that have been adapted to a more dynamic and uncertain environment.

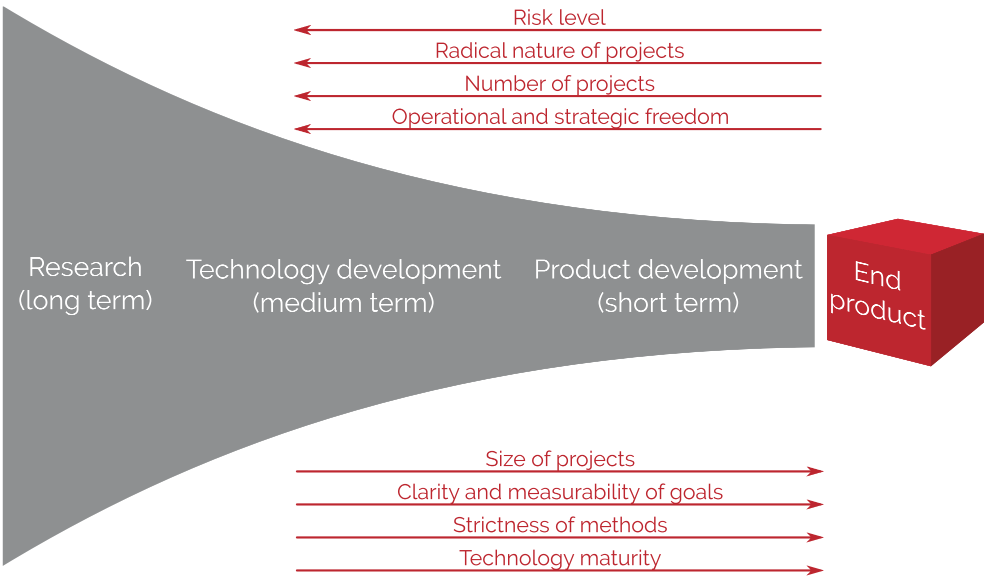


Figure 1.3: Research and technology development precede product development and carry greater risks and uncertainties than product development (Redrawn from Aalto (2004))

In this thesis, the use of architecture modelling in simultaneous Product Technology and production development is investigated. The fit of existing modelling approaches to this environment is investigated and two modelling approaches are proposed for two different uses within technology development context. Both approaches build on existing theory from literature, both are fitted to the particular problem that they are meant to solve, and both have been implemented in an industrial case.

1.1.1 Definition of technology in this thesis

Before proceeding, a definition of the following terms is in order. Technology is a key theme in this thesis and is defined here from a perspective of technology development. This means that no attempt is made at providing a universally applicable definition, but rather to provide a definition that should enable the reader to understand the perspective taken on the development of a technology within this thesis.

Definition: Technology

The application of an artificial arrangement of a collection of natural phenomena to fulfil a purpose or set of purposes

A technology is composed of a collection of Product Technologies that together can be physically realised in a product that fulfils an intended purpose.

Definition: Product Technology

A particular way in which natural phenomena can be utilized and arranged as a partial solution to how a system can achieve its intended purpose

To fulfil the intended purpose, this collection of Product Technologies is arranged in a product and this arrangement affects the function of the product. In a set of related products, multiple Product Technologies arrangements may be possible that provide a varying set of functionalities or achievable performance. The arrangements that are within the scope of the technology development of a firm can be captured in a Product Technology Architecture.

Definition: Product Technology Architecture

A purposefully aligned description of the structure, relations, and purpose of product technologies from which a group of related products can be developed

To physically realise products based on the technology, a production system must be in place with the capability to transform input—in the form of raw materials and components—into the product. The production system comprises a collection of production technologies that enable this transformation. Often, multiple production technologies can be utilised but with a new technology, some production technologies may need to be developed—either from scratch or as a further refinement of existing production technologies. Production technology, within this thesis, is defined as follows.

Definition: Production Technology

A particular way in which natural phenomena can be utilized to transform physical inputs into elements of a system in full or in part

Technology also contains a component of use. This is, for the sake of completion, termed *use technology* and defined below. Although the applications of the technology being developed are discussed in this thesis and can be seen as forms of *use technologies*, the term is not used to a great extent in this thesis.

Definition: Use technology

How the natural phenomena can be arranged—potentially with other phenomena—and be put to use within society

1.2 Scope of thesis

Product Technology and production development in a technology development context represents an area that is too broad to be researched—if the scope of the research is not delimited. The research focus within this project has been on the early phases of architecture based simultaneous Product Technology and production system development, where neither the product nor the production architecture are completely defined and the degree of technology novelty is high. This delimitation means that the focus can be maintained on subjects that are relevant with the environment of the research project. The architecture approach stems from the aim to develop a broad foundation for future products and as the applications for the technology were uncertain it was deemed imperative to avoid developing technical solutions that would only be relevant in a narrow set of applications. During the research project, areas that are relevant from both academic and industrial perspectives have been identified and covered. As the research was performed within an industrial environment during which the development project being followed progressed and entered new stages and challenges, a purely theoretical approach aimed at explaining the situation at the outset of the project would have had little practical value for the industrial participants at the end of the project. On the other hand, a purely practical approach would have had neither a rigorous foundation for the research findings nor much likelihood of providing other than anecdotal evidence for academia. A balance between these two extremes has been sought throughout the research project, where practically applicable tools have been developed on the basis of theory from academic literature with a focus on recording academically relevant empirical data along the way.

The research is framed by the use of modelling within concurrent multi-product and production development and its foundation lies in systems theory and Theory of Technical Systems (Hubka and Eder, 1988). Theories concerned with architecture based development are at the core of this research and are supported by theories on dealing with e.g. uncertainty in development, product and production development. The research covers what should be modelled and in this regard reaches into literature on the use of modelling in NPD for insight and inspiration.

Modelling within engineering design can take many forms. The modelling dealt with in this thesis is architecture modelling, based on system modelling. While a variety of other modelling types can also be valuable in an early phase they lie outside the scope of this research and are only covered superfluously in supplemental form. The research is performed at a mechanical engineering department and the background of the researcher is primarily within mechanical and industrial engineering. Therefore, the perspective of this research and much of the literature covered is rooted in these domains. However, the research is based on methodologies from the engineering design research community that have been applied successfully on products combining software, electronics, and mechanics and within a variety of scientific disciplines (Blessing and Chakrabarti, 2009).

1.2.1 Empirical data

The industrial focus of the thesis is on early phase platform based design, within an interdisciplinary technology development environment but with a predominantly mechanical engineering focus. Most of the research was performed over a three year period within a multi-product development project using a platform based approach concurrently with production, material, and application development in a technology development setting. The project included multiple collaborating organisations but the research focused on the efforts of a central firm that was developing a platform based on a new technology. Industrial experts outside of the firm, both project participants from collaborating organisations and from organisations external to the project have been interviewed to gain a broader understanding of the research phenomena.

1.3 Research objectives

The research objectives were to identify opportunities for applying architecture modelling to support development and decision making related to technical capabilities in an early phase of simultaneous Product Technology, production and technology development. The development activities and decisions in focus are those that determine the functional and structural aspects of the Product Technology and production architectures and their influence on the firm's ability to develop product platforms based on new technologies.

To investigate how methods or approaches from mature product development could be adapted for use in technology development.

Finally, to investigate how implementing such approaches in technology development can support development and decision making.

1.3.1 Research Questions

Stating Research Questions (RQs) serves two purposes: to guide the research towards a meaningful result, and to communicate what the research is meant to answer—to other people.

In technology development, the solution space for the architectures being developed is vast and little has been defined regarding them. However, the resources to develop the architectures are limited and decisions have to be made that determine what capabilities the resulting Product Technology and production architectures will be able to offer. The research in this project can be described as having dealt with a broad theme: *How can architecture models support platform development in a technology development context?* However, this is too broad to be a research question—but it defines the main theme.

As part of clarifying the research context and as an underlying theme throughout the research project, characteristics of technology development that affect architecture modelling in these early phases of development have been sought and identified. This identification provides insight into the context and purpose of the research, what the requirements architecture modelling in such a context are and what adaptation—if any—is necessary for a successful implementation of architecture modelling within that context.

> **Research Question 1** How do the technology development activities and context during simultaneous product technology and production development affect architecture modelling in terms of what to model, what the model focus should be, and what goals should be supported by the models?

There are two main research questions regarding architecture modelling in this project, where each has focus on its own application area of architecture modelling within a technology development setting: Product Technology Architecture modelling and Production Architecture modelling. They are interrelated as these represent two central themes within technology development. Each of these research questions is accompanied by supplementary research questions—these are presented alongside their corresponding main research question

Product Technology Architecture modelling Research question 2 deals with Product Technology Architecture modelling in an early phase of development. Within more mature NPD, architecture models have proven their value in supporting multi-product development by structuring the solution space—which in turn helps defining and structuring the development tasks.

> **Research Question 2** How can a Product Technology Architecture be modelled during technology development as a way to structure the development of a foundation for multiple product platforms?

This is a rather broad RQ and therefore supplementing RQs are formulated. To be able to model a Product Technology Architecture, it must be defined what its contents should be, how the contents can be modelled and how the model can support Product Technology Architecture development within a technology development setting.

> **Supporting Research Question 2.1** What can be constituted as relevant modelling elements to be included in a Product Technology Architecture model during technology development, where the product and production architecture descriptions are not yet complete?

While product architecture models have been developed and applied in more mature NPD and may provide insight into what constitutes a complete architecture model, it is not certain what elements of a product architecture are fit for inclusion in a Product Technology Architecture model. RQ2.1 addresses the identification of fitting modelling elements.

> **Supporting Research Question 2.2** How can the functional aspects of a product architecture be modelled during technology development in such a way that a Product Technology Architecture's capabilities can be discussed and communicated with stakeholder groups in support of the development of the Product Technology Architecture?

RQ2.2 addresses the functional aspects of the Product Technology Architecture—how to model what the Product Technology Architecture 'can do'. Both within the technology development and afterwards, the contents of the Product Technology Architecture should have a purpose, which the contents can fulfil by providing functionality. How this can be modelled before a complete product architecture description is available must be identified.

> **Supporting Research Question 2.3** Through what mechanisms can architecture models support platform development in an early phase of simultaneous product technology and production development?

RQ2.3 aims at clarifying through what mechanisms an architecture model can support platform development in a technology development setting. Such a clarification can both be of value during this research for refinement of the models and for future research on the subject.

Production architecture modelling The focus of Production Architecture development at an early phase differs from the focus in later phases. When the product architecture is more completely defined, the Production Architecture development can be focused on optimization for the intended production task. But during technology development, the structure, required capabilities, and obtainable capabilities of the Production Architecture have to be determined. During technology development neither the production architecture nor the product architecture has been completely defined but decisions still have to be made regarding investments and resource use for their development. A modelling approach meant to support Production Architecture development decisions at an early phase must fit to this uncertain environment.

> **Research Question 3** How can a Production Architecture be modelled in simultaneous Product Technology and production development to support development decisions regarding the production system architecture?

This research question focuses on Production Architecture modelling in an early phase of concurrent product and Production Architecture development. The setting—technology development—has implications on what is known and what is not known about both the Production Architecture to be modelled and the product architecture from which the products to be produced will be derived. This may have an effect on what can—and should—be modelled at this stage, which leads to RQ3.1.

> **Supporting Research Question 3.1** What can be constituted as relevant modelling elements to be included in a Production Architecture model in a technology development context, where the product and production architecture descriptions are not yet complete?

A central aim of modelling the Production Architecture is to support development of production capabilities that are fitting to the production task. This requires communication across stakeholder groups to identify what capabilities are needed and whether the capabilities of the Production Architecture fit the requirements of the technology development project. Therefore, RQ3.2 will focus on how to model the capabilities of the Production Architecture to relevant stakeholder groups.

> **Supporting Research Question 3.2** How can the capabilities of a Production Architecture be modelled during technology development in such a way that they can be communicated and discussed with stakeholder groups in support of the development of the production architecture?

As the modelling activity is meant to take place within a technology development environment, not only the contents of a Production Architecture can be assumed to change with time but also the development environment—as the development progresses. To some extent this may be handled by iterating models, but to be of value in development decisions, the modelling activity should be able to handle a time dimension, as well as a description of the Production Architecture.

> **Supporting Research Question 3.3** How can planned changes to the Production Architecture that are part of the planned development progress be taken into account in a model of the Production Architecture?

In the following text, the research questions will be addressed through describing the results of the unique opportunity of doing an depth case study in a technology development project aiming at developing the foundation of a product platform. The case study enabled access to both development activities and key stakeholders in the technology development activities over a period of three years.

1.4 Thesis outline

Chapter 1 has introduced the research subject, its background and the scope of the thesis. Chapter 2—Research approach—presents the research approach—the research objectives and research questions, the research methods adhered to, research verification applied, and activities performed during the course of the research. Chapter 3—Theoretical basis—describes the theoretical basis on which this research is founded. The case project background and progress is described in chapter 4—Case study. The results of this research have been published in papers that are discussed, and reflected upon, in chapter 5—Research and results. Finally, chapter 6—Conclusion—presents the conclusions of this research, identifies the core contributions, provides an evaluation of the research performed and the limitations of its results, evaluates the impact of the research on both academia and industry and provides suggestions for further research. The references cited in this thesis are listed in the bibliography from page 105. A glossary containing an overview of key terms and abbreviations is placed as the last part of the front-matter, before the introduction.

CHAPTER 2

Research approach

Research is formalized curiosity. It is poking and prying with a purpose. It is a seeking that he who wishes may know the cosmic secrets of the world and they that dwell therein.

—Zora Neale Hurston, *Dust tracks on a road*, p. 182 (1969)

This chapter presents a description of the research approach during this PhD project. Section 2.1 describes the theoretical background for the research methods applied in the PhD project. Section 2.2 describes the theoretical basis for the verification of the results obtained in this research. The particulars of the research approach, my role as the researcher, and the primary data sources are covered in section 2.3.

2.1 Research methods

The *theoretical framework* on which this research is based can be described as the wide range of research on architecture modelling and its usefulness in an industrial context—building on the theoretical foundation of Theory of Domains, Theory of Technical Systems, and the Genetic Design Model System—further described in chap 3. The *methodology* followed is the Design Research Methodology, which is described in section 2.1.1, combined with an Action Research approach described in section 2.1.2. The *area of concern* is the simultaneous Product Technology and production development in a technology development context and is described in more detail in chapter 4.

2.1.1 Design Research Methodology

Blessing and Chakrabarti (2009) proposed the Design Research Methodology as a framework for studying phenomena in design that is aimed at supporting systematic research into engineering design. It represents a systematic approach to developing research based support methods and tools for implementation in industry and evaluating the effectiveness of their implementation—which is a fitting description of this research. The framework—as

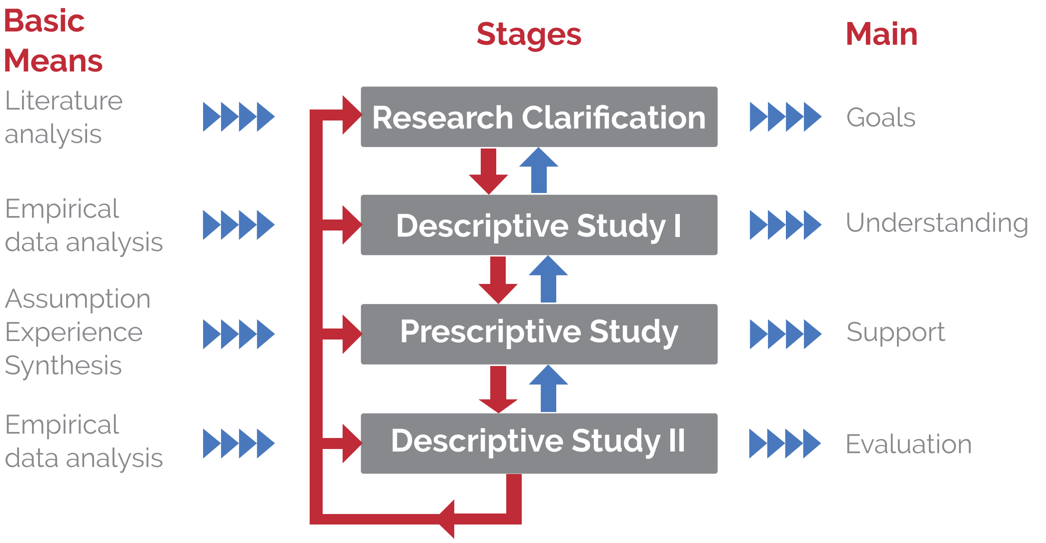


Figure 2.1: The basic means, stages, and main outcomes in the Design Research Methodology framework (redrawn from Blessing and Chakrabarti (2009))

illustrated in figure 2.1—presents four stages of research; starting with Research Clarification (RC), which clarifies the goals of the research, progressing into Descriptive Study I (DS-I), aimed at improving the understanding of the situation to be supported, followed by Prescriptive Study (PS), in which support is developed and implemented in the intended environment, and concluded with Descriptive Study II (DS-II), in which the effect of implementing the support is evaluated.

Not all research projects follow all stages, not all stages are necessarily followed to the same depth, and the stages may be iterated to improve the rigour of the research. The Design Research Methodology framework describes 7 types of research projects, as project stereotypes. This research project falls within type 3, where an RC, a review-based DS-I, and a comprehensive PS have been performed, along with an initial DS-II, in a concurrent, iterative process. Not all stages have been performed to the same depth, as a practical approach was necessary to be able to implement support in the case project in those phases where the support was needed and to be able to evaluate the effectiveness of the support. Furthermore, several iterations between PS and DS-II have been performed, in accordance with the Action Research methodology—which encourages an iterative process of implementing the developed support, evaluating its effect, refining it on the basis of the evaluation, and repeating the process.

2.1.2 Action Research

This research has been based on an Action Research approach, where the researcher takes an active part within the environment where the research takes place—the area of concern. This approach breaks with the conventional—positivist—view of the role of the researcher as an observer that abstains from direct influence during an experiment. Checkland and Holwell (1998) maintain that the following describes all research: Research contains a framework of ideas, is based on a methodology, which is applied in an area of concern, and yields learning about not only the area of concern, but also the methodology and the framework of

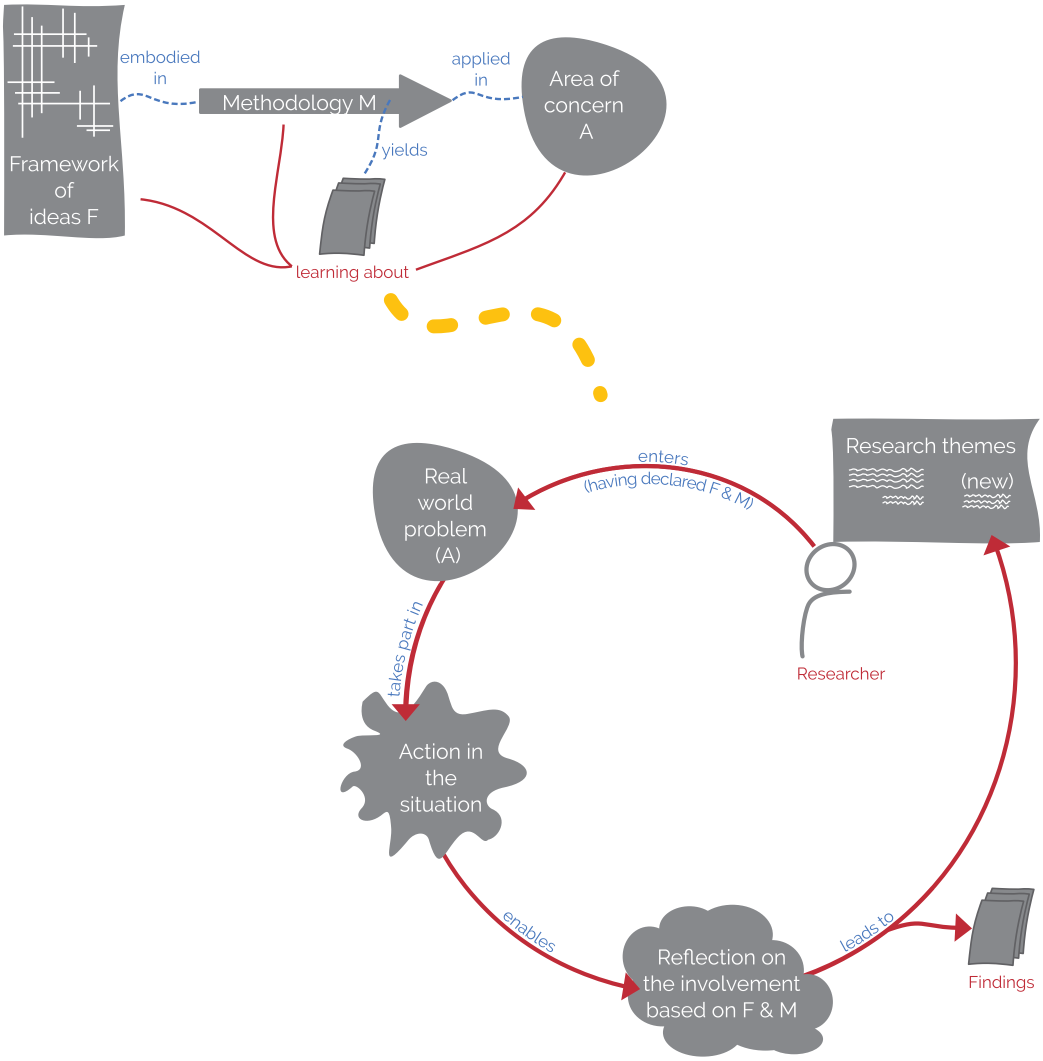


Figure 2.2: Elements that are relevant in any research and are also represented in Action Research (adapted from Checkland and Holwell (1998))

ideas. As illustrated in figure 2.2, these elements are also represented in Action Research, but instead of being a passive observer, the Action Research researcher actively participates in the actions being taken within the research environment and thus takes on a dual role—as both a participant and a researcher. Action Research is seen as an iterative research process—echoing the message of Design Research Methodology—where each iteration builds on the previous one. This is illustrated in the Action Research process in figure 2.2 in the spiral form of the Action Research process—increasing the knowledge base with each iteration.

2.2 Research verification

Rykiel (1996, p. 233) stated that validation "indicates that the model is acceptable for use, not that it embodies any absolute truth, nor even that it is the best model available". Validation of a support is based on its performance within—and how well it fits—its intended application. Validation can take many forms, but not all validation methods are fitting for use within the setting of this research. The support developed in this research is not a simulation of a real system, which eliminates the possibility of comparing the output of the support to the results in the real system. However, some of the validation techniques covered by Rykiel (1996), who focused on validating ecological models, may be applicable within design research:

- *Conceptual validity:* Are the theories and underlying assumptions justifiable and the representation in the support reasonable for its intended use?
- *Face validity:* Do knowledgeable people regard the support reasonable?

Buur (1990) presents two perspectives on verification of design research: logical verification and verification by acceptance. These entail the following acceptance criteria:

- *Logical verification*
  - The theory has internal consistency—the elements of the theory are not in conflict with each other
  - Completeness
  - In agreement with theory
  - In agreement with practice
- *Verification by acceptance*
  - Statements are accepted by practitioners
  - Models and methods are accepted by practitioners

It is worth noting that both Rykiel (1996) and Buur (1990) consider the consistency of the theory contained within the research and acceptance by individuals with an understanding of the research or application area to be criteria for validation. However, Buur's validation framework is aimed a validation of a theory on design, which is not the primary aim of this research.

Yin (2009) argues that case studies can be valuable research tools in descriptive research and Voss et al. (2002) argue their merit with operations management—a research area that is related to design research. Yin (2009) discusses four criteria for validation of case study results:

- Construct validity
  - Are the results based on a solid foundation?
  - Supported through use of multiple data sources
- Internal validity
  - Can causal relationships be established?
- External validity
  - Can the results be generalised?
- Reliability
  - Can the case study results be repeated?

Voss et al. (2002) emphasize qualitative data as key element in establishing *internal validity*.

Blessing and Chakrabarti (2009) focus more on validating support developed within a research project. They presented three central elements of evaluating research where support has been introduced into an area of concern:

- *Usability:* Can the support be used for the intended task?
- *Applicability:* Does the support address key factors in the intended application area?
- *Usefulness:* Does the support have the ability to realize the expected impact?

Blessing and Chakrabarti's validation framework is applied on the modelling frameworks and Yin's validation framework is applied on the descriptive part of this research in section 6.2.

2.3 Research activities

This research was performed as a single case study over a three year period in an industrial setting in which real-time data collection methods were used. A leave of absence was granted for two distinct periods, which enabled the research to stretch over the end of the case project. The case study followed a mixed Action Research and Design Research Methodology based approach, where Design Research Methodology provided the framework and was supplemented by Action Research. In accordance with an Action Research approach I entered into the case project in a participatory manner and instigated actions during the research. These actions had an effect on the area of concern that might not have been realized without my interventions (Schein, 1995). While this is considered a drawback in positivist research, this enables the Action Research researcher to participate in action and act as an agent of change (Coughlan and Coghlan, 2002)—e.g. by implementing a support developed in the research project.

I took on the Action Research role of a process consultant (Coughlan and Coghlan, 2002) in the case project, where I could participate in the project work and initiate improvement actions based on literature and my observations—inside a project group tasked with developing a product platform in a technology development project. This enabled real-time observation of events as a participatory observer, but practically eliminated the possibility of acting as a passive observer except in a few isolated situations. Figure 2.3 shows how the research progressed into new research stages. While not illustrated in figure 2.3, the research also iterated between research stages, especially between PS and DS-II, where each iteration can be said to have corresponded to an Action Research cycle—comprising a sequence of data gathering, data feedback from participants, analysing data, planning action, taking

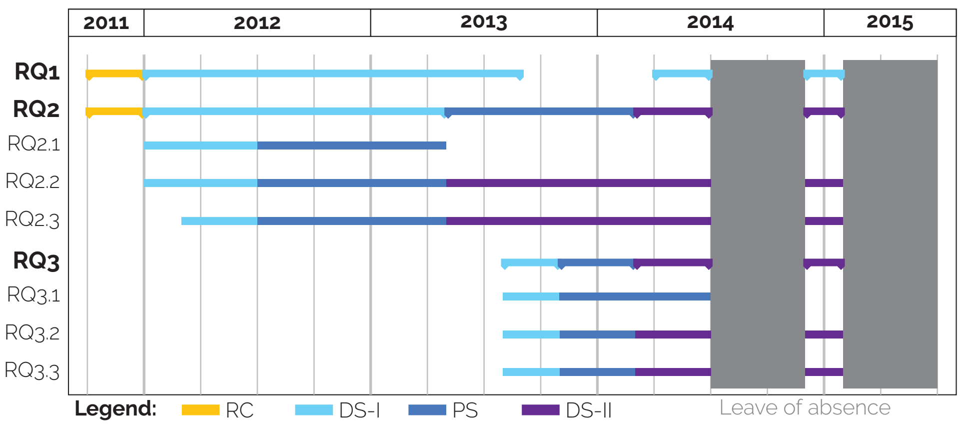


Figure 2.3: The research process in the PhD-project

action, and evaluating the effects (Coughlan and Coghlan, 2002). However, not all iterations were equally rigorous due to time constraints, new findings, or due to events in the project that necessitated a flexible approach to the research. This is in line with Coghlan (2004) who noted that Action Research cycles can vary in length and that a project may comprise both cycles of varying lengths and concurrent cycles—these may be linked to events in the project and be the result of dealing with uncertainty in the Action Research research. The potential necessity and value of goal oriented and opportunistic behaviour on the part of the researcher, while performing real world research within the Design Research Methodology framework, is also acknowledged by Blessing and Chakrabarti (2009, p. 17).

This research relied almost solely on qualitative data. While quantification of some aspects of the project could be analysed by quantifying e.g. tasks and challenges found in project documents, this was only feasible when reaching the end of the research project—as this type of data was continually being created during the project. The primary goal of this research was to develop and implement support in the project, hence, data analysis based on data that was not available until the end of the project did not have a high priority.

The primary data sources in the case project were:

- Participatory observation
  - Real time observation of events and behaviour
  - Both in formal and informal settings
    * Over one hundred formal meetings and workshops attended in the case project
    * Daily activities with key stakeholder for over two years with a shared office
- Observations of the use of the support
- Interviews with stakeholders that used the support
- Project documentation
  - Complete access to project documents, including review documents, meeting minutes, and reports from all Work Packages and all levels
  - Presentations from meetings and symposiums
  - Technical documents

Interviews with external parties In addition to interviews and informal communications with the stakeholders in the case project, interviews were performed with three individuals that were outside the case project and two individuals that were not part of the platform development in the case project—as part of DS-I to clarify the context within which this research is performed. The interviewees were:

- External
  - A mechatronics professor with expert knowledge on design and construction of mechatronic systems
  - A professor in automation with 10+ years of experience in integrating transducers in automated equipment
  - The head of new technologies of a leading medico company
- From the DEAP project
  - A product development consultant and entrepreneur with 20+ years experience with product development in various firms and industries

An R&D manager in a firm producing products based on technology development

The aim of these interviews was not to gain a complete overview of all aspects of technology development but to get a broad outside perspective of challenges and goals for product development in a technology development setting. The interviews were semi-structured and adapted to the individual being interviewed.

Thematic analysis of project documents Thematic analysis was performed on 138 monthly reports from the application Work Packages from the DEAP project for paper A. Figure 2.4 illustrates the research method followed for this paper.

Figure 2.4: The research approach for a thematic analysis on 138 monthly reports from the DEAP project (Redrawn from paper A)

2.3.1 Research plan

Figure 2.3 shows how and when research questions were covered in the research stages of Design Research Methodology. Several DS-I ↔ PS ↔ DS-II iterations were performed, where each iteration provided opportunity for refinement.

Research Clarification (RC) The RC stage addressed clarifying the context of the environment in which the research was performed, setting goals for the research and its focus, and developing the research questions. RQ1 and RQ2 were partially addressed in the RC stage.

Descriptive Study I (DS-I) The DS-I stages focused on gaining an in depth understanding of the context of the research, the requirements of the case project for architecture modelling, and identifying what to address with the architecture models implemented in PS stages. This was achieved through a comprehensive literature study complemented by observations from the case project, interviews with external parties, and thematic analysis of 138 monthly reports from application Work Packages.

Prescriptive Study (PS) A comprehensive PS was performed in an iterative process where the PS stages comprised the development of architecture models and their implementation in the case project. Several iterations were made and followed up by initial evaluations in a DS-II stage. These iterations were both necessary and valuable as there was a need in the project for a model from an early phase and the subsequent iterations provided opportunity to refine the models based on the evaluations in the DS-II stages.

Descriptive Study II (DS-II) Initial DS-II stages were performed repeatedly during the research as iterations were performed on the architecture models. The evaluation in DS-II stages focused on the usefulness of the architecture models—whether they provided the intended support in case project.

2.3.2 Other research activities

International & national research collaboration The research has benefited from collaboration with researchers in various fora in both a national and international setting. The product architecture group—within which this research was performed—provided a constant forum for discussions.

Courses abroad—and those with a high number of international PhD-students—provided a forum with new perspectives through dialogue surrounding both my own and others' research. Other courses have introduced me to surrounding research subjects and researchers. Conference attendance provided another forum for inspiration and dialogue on research on both engineering design and DEAP transducer.

A short external research exchange was performed by visiting Professor Mitchell Tseng and his research group at the Hong Kong University of Science and Technology. This opportunity to discuss my research with a distinguished Professor within product family architecture development—with a notable track record from industry—gave me new insights surrounding my research topic, my research approach, and communicating my research.

Conferences Conferences attended during the PhD-studies:

- Produktudviklingsdagen 2011, Kgs. Lyngby, Denmark
- Produktudviklingsdagen 2012, Kgs. Lyngby, Denmark
- Electroactive Polymer Actuators and Devices (EAPAD) 2013 in San Diego, Ca, USA
- International Design Conference—DESIGN 2014 in Dubrovnik, Croatia

Teaching During the PhD-studies I have acted as assistant teacher and guest lecturer in three different subjects:

- Technology platforms and architectures—Assistant teacher: 2012–2014
- CAD for design engineers—Assistant teacher for a few lessons
- Mechatronics Design—Guest lecture & exercise session

PhD-courses Courses taken during the PhD-studies:

- *Research and PhD-studies at DTU Management*—DTU course on how to do research and a PhD project
- *Management in Science and Innovation* — DTU
- *Teaching and Learning*—DTU
- *Recent Research Results in Management Science*—DTU
- *Strategic Foresight in Engineering*—DTU

- *Special Course in Systems Engineering*—DTU
- *Summer School on Engineering Design Research*—DTU, Technical University of Ilmenau & Université du Luxembourg

CHAPTER 3

Theoretical basis

Dilbert: You joined the "Flat Earth Society?"
Dogbert: I believe the earth must be flat. There is no good evidence to support the so-called "round earth theory."
Dilbert: I think Christopher Columbus would disagree.
Dogbert: How convenient that your best witness is dead.

—Scott Adams, *Dilbert comic strip* (9 Oct 1989)

This chapter describes the theoretical foundation for this research—both in terms of literature on which the modelling frameworks developed are based on and in terms of related literature that has supported the framework development and covers the following subjects:

- Technology development as an uncertain undertaking supported by gradual alleviation of uncertainties through iterative development and testing.
- Describing a product or a system through systems theories and how these aim to look further than simply at the physical description of a product.
- Product architecture is introduced as a widely used phenomenon in both industry and academia to support systematic development of products.
- The application of product architecture on multiple products—product families—and this thesis' foundation for multi-product architectures modelling is described.
- Production architecture as a subset of system architecture.

3.1 Technology development

In the introduction, it was discussed how technology development provides a foundation for new products and a competitive advantage for the firm. However, before this foundation has been developed, technology development faces uncertainties on a variety of levels. The Technology Readiness Level is an approach to assess the maturity of a technology under

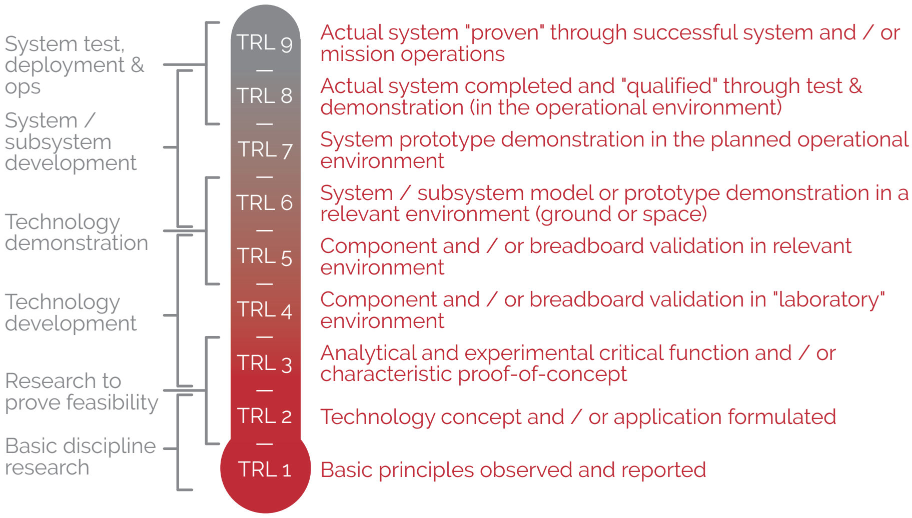


Figure 3.1: The Technology Readiness Level scale defines nine levels of readiness that define how mature the technology is for a particular application (Redrawn from Mankins (2009))

development under the premise that the goal of the technology development is a utilization of a phenomenon in an actual system in its intended environment (Mankins, 1995). The Technology Readiness Level scale is illustrated in figure 3.1. According to Mankins (2009) successful deployment of new system capabilities relies on "the prior success of advanced technology research and development efforts"(p. 1216). Technology assessment methods—such as the Technology Readiness Level assessment—are used to assess technology development progress and whether a new technology is ready to be integrated into new products (Corin-Stig et al., 2015). As technology maturity advances—e.g. as higher Technology Readiness Level levels are reached—the technology uncertainties are reduced; the knowledge of what is obtainable and how to obtain it is increased. With higher technology novelty—lower Technology Readiness Levels—there is generally higher risk and longer lead times (Mankins, 1995; Tatikonda and Rosenthal, 2000).

The higher the technology uncertainty, the greater is the importance of testing—performing experiments to ensure that the designed quality matches the production capabilities (Swink, 1999). Testing activities in relevant settings increase the chances of identifying problems and benefits of new technologies. The level of uncertainty is high in the early phases of technology development but iterative experimentation can alleviate uncertainties (Högman, 2011; Mankins, 2009). New technologies tend to have limited uses at first, but as time progresses—with solutions on the market—unanticipated contexts for their usefulness often arise (Rosenberg, 1996). With knowledge of more fitting applications, better decisions can be made regarding the development task—better prototyping capabilities can enable more extensive testing in potential applications. To be able to test a new technology in diverse applications, however, the technology needs to be flexible—developed on a robust foundation fitting to multiple potential application requirements rather than developed in a trial and error process aimed at constructing a single purpose system (Clausing, 1994)—technology development should be decoupled from individual applications. Identifying, testing, and improving generic performance factors increases the robustness of the technology development—the ability to develop products based on the technology that meet application requirements within a wide range of conditions (Taguchi et al., 2004a).

Contribution to this research Technology development carries uncertainty and risk—both concerning technology performance and its applications. These uncertainties can be handled by assessing and monitoring technology development, through extensive testing, and by decoupling technology development from individual applications. As technology development is a broad subject, this section has only scratched the surface of relevant literature but doing so provides a background for the context of use for the developed modelling approaches.

3.1.1 Production capabilities in a technology development context

To be able to test the technology during development, the necessary production capabilities must be in place. Prototyping capabilities are determined to a large extent by the production capabilities. The production system determines the obtainable product quality (Skinner, 1985) and production flexibility determines the range of product variants that can be produced (Boyle et al., 2002; Jain et al., 2013)—determining the obtainable product quality and range of prototypes that can be tested within the firm and with external partners. Full production capabilities cannot be at hand from the outset of technology development and uncertainties limit the degree to which production capabilities can be implemented during development. Yet, to investigate whether scaling up the production of the technology, it is imperative to test production on equipment that is comparable to that used in industrial production (Galagan et al., 2011). In production of mature products, implementation of fitting production flexibility is advised—as flexibility comes at a cost (Boyle et al., 2002; Matta et al., 2010). During technology development this may be rephrased as implementation of fitting production capabilities. Any implementation of production capabilities requires an investment—implementation of capabilities during uncertainty should be delayed until they are needed (Jain et al., 2013).

Contribution to this research Production capabilities that enable determination of obtainable product quality can be implemented as technology development progresses. Having in place the capability to produce prototypes in a suitable quality facilitates testing of prototypes—which in turn supports technology development—and developing production technologies can be a necessary step towards future commercialisation of products based on the technology being developed. The flexibility of the implemented production equipment needs to be suitable to the uncertainties in place regarding future product design and features.

3.2 Systems theories

3.2.1 Theory of Technical Systems

The Theory of Technical Systems set forth by Hubka and Eder (1988) describes products—and production systems—as technical systems. They defined these technical systems as a subset of artificial systems, which are distinct from natural systems.

In a transformation system as viewed in the Theory of Technical Systems, an operand undergoes a transformation from an existing state to a desired state through a transformation process. The transformation process, as is shown in figure 3.2, takes place within an environment and is acted upon by operands—human, technical, information, and management & goal systems.

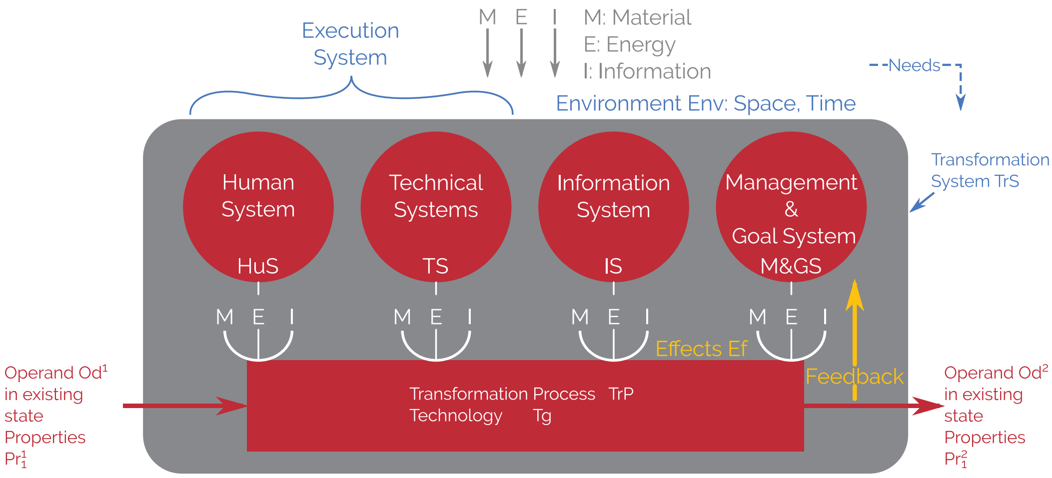


Figure 3.2: A model of the transformation system according to the Theory of Technical Systems (Redrawn from (Hubka and Eder, 1988))

The Theory of Technical Systems defined four domains that form an integral part of later theories in design: transformation, function, organ, and component domains. In the Theory of Technical Systems, *technology* is considered as belonging to the transformation process, but this view does not coincide with the use of the term Product Technology in this thesis.

Contribution to this research The Theory of Technical Systems contributes to this research with a perspective from which technical systems can be seen and understood. Furthermore, as it is the foundation for many later contributions on architecture modelling, it represents the fundamental theory against which modelling contributions can be measured.

3.2.2 Theory of Domains

Andreasen (1980) developed the Theory of Domains on the foundation laid by the Theory of Technical Systems. In the Theory of Domains, three interrelated domains—the activity, organ, and part domains as illustrated in figure 3.3—that each provides a particular perspective on the artefact under consideration—the product. The function domain of Theory of Technical Systems is here considered to relate to the three defined domains—not to be a domain in itself. Through these three perspectives, the Theory of Domains provides a framework for viewing a product that emphasizes not only the technical construction—the part domain—but also the use of the product—the activity domain—and its functionality—the organ domain.

The *activity domain* describes the use of the product through individual technical activities and how the sequence of activities lead to the transformation of the operand from its undesired state to its desired state. It is not a description of the activities within the product but the activities that the product is involved in—for a drill, it is the creation of holes in the wall and not the rotation of the drill.

The *organ domain* describes the function elements of the product itself and the organ structure defines how the system of functional elements form the effect needed for the activity—the rotation of the drill and its material removal function is in focus here.

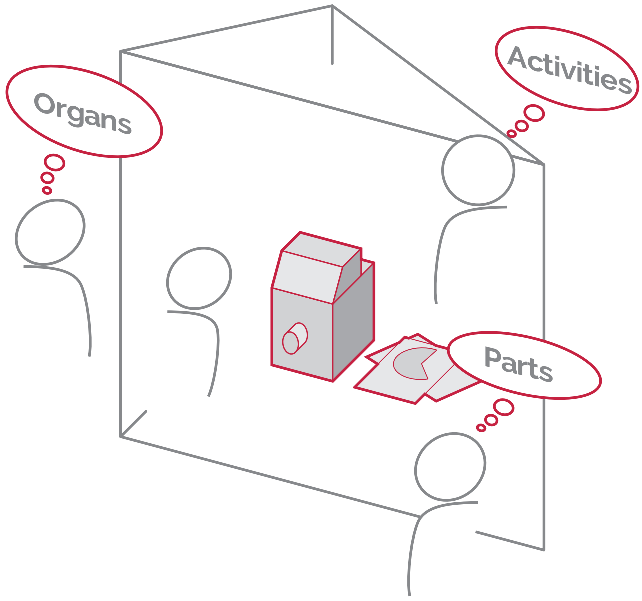


Figure 3.3: The Theory of Domains proposes that system models covering three perspectives are necessary to capture product synthesis: organs, parts, and activities (Redrawn from Andreasen et al. (2015))

> An organ is a function element (or 'means') of a product, displaying a mode of action and a behaviour, which realise its function and carry its properties
> *(Andreasen et al., 2014, p. 179)*

The *part domain* describes the physical parts that comprise the product, along with their interrelations defined through interfaces. Parts can be active and interact with other parts through their interfaces and together they physically realize the organ structure of the organ domain—this is the drill itself and the individual parts of the motor that provide the rotational effect.

A product can be described both at a varying level of abstraction and varying level of complexity. This effect is illustrated in figure 3.4b. A product often becomes more concretely defined while going between the domains as product development progresses. The function-means tree shown in figure 3.4a is an illustration of a hierarchical definition of a product that switches between domains at each level, starting with a function (a desired effect) which is solved with a means (organ). This process continues through sub-means and sub-functions until the product is fully defined.

Contribution to this research The theory of domains contributes to this research by defining three perspectives from which a product should be described. Distinguishing between activities in which the product is used, and internal functions, defining organs as function carriers, distinct from, but realized by parts and defining parts as belonging to their own domain provides a valuable perspective for modelling within technology development contexts. The function-means tree can be seen as a hierarchical representation of the design rationale through effects and organs—it provides a conceptual inspiration for viewing partial technological problems within a technology development context.

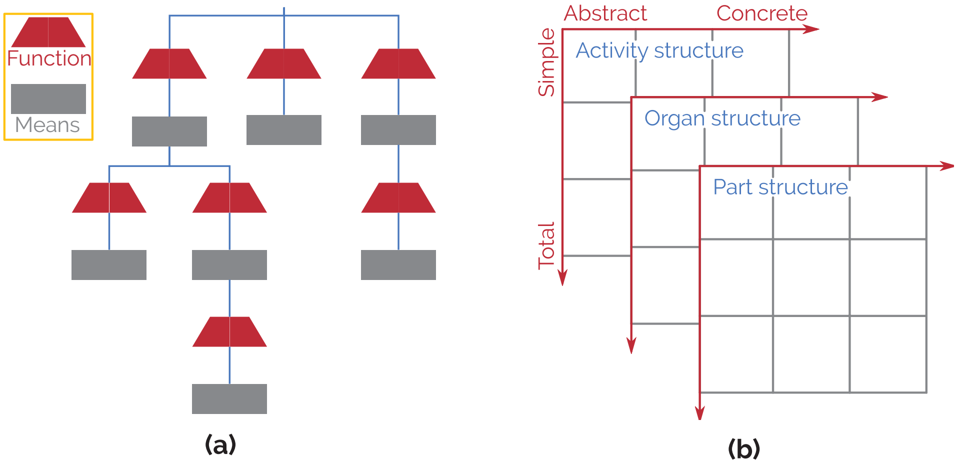


Figure 3.4: The function-means tree (3.4a) is related to the level of detail to which the product has been described (3.4b) (Adapted from (Andreasen, 1980))

3.2.3 Theory of dispositions

Each activity in the design of a product can have dispositional effects on other activities in other life cycle phases of the product. Olesen defined these dispositions in his PhD thesis:

> By a disposition we understand that part of a decision taken within one functional area which affects the type, content, efficiency or progress of activities within other functional areas.
>
> *(Olesen, 1992, p. 53)*

All life-cycle phases are affected by decisions in earlier life-cycles—product design affects e.g. production, sales, installation, operation, service, scrapping, recycling and deposition. The effect is called the dispositional effect as the decisions causing the effect are made at a considerably earlier time than when the effect is realized.

Contribution to this research Contributed to the research through the emphasis on dispositional effects of decisions—routes taken during the project—on both platform and production system capabilities and their interrelations. The dispositional effect is no less important to take into account during technology development—where the route to the end-user is even longer than in more mature NPD.

3.2.4 Genetic Design Model System

Mortensen (1999) developed the Genetic Design Model System—which builds upon the theory of domains to provide a framework for modelling a product through the use of four different modelling classes: constitutive/behavioural models, soll/ist models, core/view models, and design/life phase models. The modelling classes are represented in the chromosome model illustrated in figure 3.5, which is a refinement of an earlier chromosome model (Ferreirinha et al., 1990).

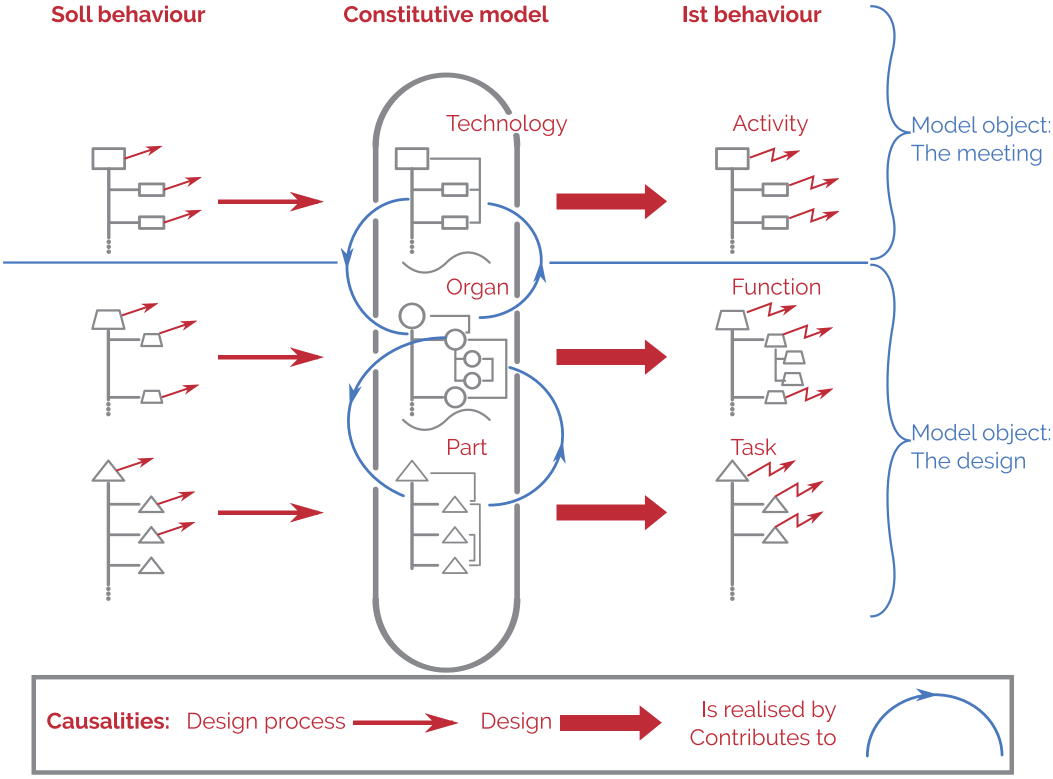


Figure 3.5: The chromosome model contains both constitutive and behavioural aspects of the product (Redrawn from Mortensen (1999))

Constitutive models define the design of the product, while *behavioural* models define the behaviour of the product. By this distinction, *characteristics* define the constitutive description of the product—its structure, elements, and their relations, while behavioural models define both *inherent properties* of the product—e.g. strength and weight—and *relational properties* of the product—e.g. cost and quality. The constitutive parts of the Genetic Design Model System are the technology, organ, and part models, while the behavioural models are represented by the soll/ist models. Causal relations between technology, organ, and part models indicate that e.g. technology is realized in organs and organs comprise parts.

Soll/ist models are two distinct behavioural models describing the product. Both describe the behavioural aspects of technology, organ, and part models—activity, function, and task, respectively. The distinction between *soll* and *ist* models lies in the difference between the intended and actual behaviour of the product:

Soll describes the intended behaviour—the goal of the product development, articulated as requirements.

Ist describes the actual behaviour—the result of the product development, articulated as actual properties.

While soll can be linked to the requirements of the product and differences between soll and ist can in some cases be described as unfulfilled requirements—or a lack in requirement fulfilment—the difference can also lie in secondary behaviour undefined by the requirements.

For example, on an abstract level, the soll behaviour of a lifting device is to transport an artefact vertically from one position to another. The ist behaviour may fulfil this but additionally produce heat and noise through friction that may or may not be defined in the soll behaviour. Achieving a suitable match between the soll and ist behaviours through modification of characteristics can be seen as the goal of product development (Weber, 2014).

The life phase view of the Genetic Design Model System is represented by the top part of the soll/ist and constitutive models—modelling the meeting between the product and its life phases. The design of the product is described in the two lower levels—part and organ—where both the physical realization and functionality of the product are defined.

The core model comprises the part model onto which multiple organ views can be superimposed—as the part model defines the materialization of the product. Superimposing multiple organ views onto the core model can be valuable as organ views can require multiple perspectives to fully describe a product, such as hydraulic, pneumatic, and fluid dynamic organ views.

Contribution to this research The Genetic Design Model System contributes to this research by defining both behavioural and constitutive models as distinct aspects of a product model. Defining the modelling elements for a product within both behavioural and constitutive modelling classes at three distinct levels—each with focus on a particular domain—contributes to an understanding of the product and the causalities that are central to how a product provides value in its operation. Furthermore, the distinction between *soll* as the goal of engineering design and *ist* as the achieved result provides both a theoretical and operational theme with which technology development aims and progress can be understood.

3.3 Product architecture

The term product architecture is widely used in literature and multiple definitions exist. Ulrich defined product architecture as:

> “(1) the arrangement of functional elements; (2) the mapping from functional elements to physical components; (3) the specifications of the interfaces among interacting physical components.”
>
> *(Ulrich, 1995, p. 420)*

This definition emphasizes structure, function and the interfaces among physical components of the product architecture—their relations. Other definitions do not explicitly state physical components. Sanchez presented product architecture as “a system of interrelated functional components” and that the product architecture is created by the decomposition of the product into “a system of functional components” and those components’ interactions “have been fully specified”(2000, p. 613). Crawley et al. took a similar approach:

> “System architecture is an abstract description of the entities of a system and the relationships between those entities.”
>
> *(Crawley et al., 2004, p. 2)*

A different approach to architecture definition was taken by Andreasen et al., who emphasized purpose within the product architecture by stating that:

> An architecture is a purposefully aligned structure of a system.
>
> (*Andreasen et al., 2004, p. 2*)

The purposefully aligned structure emphasizes the importance of dispositional effects across life-cycle phases of the product.

As illustrated in figure 3.6, the dispositional effect of decisions during product architecture development on e.g. the assembly system architecture can be controlled through rule based alignment of the product and assembly system architecture.

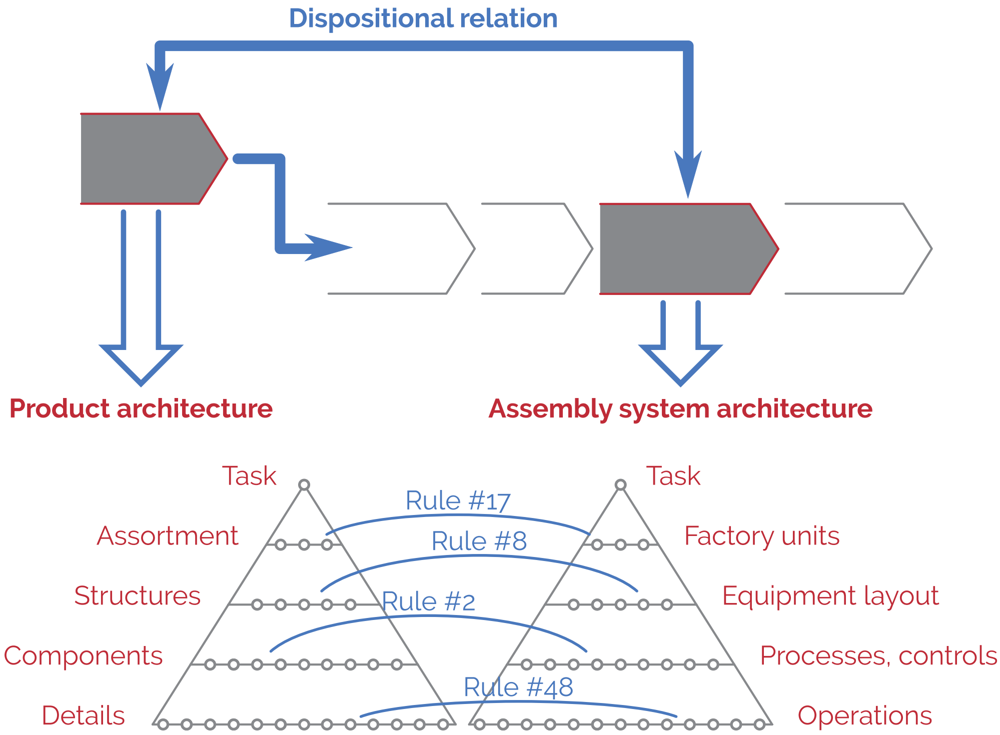


Figure 3.6: Alignment of architectures reduces unintended dispositional effects (Redrawn from (Andreasen et al., 2004))

The logic behind the product architecture can have a profound effect on the dispositional effect. Product architectures can be defined as integral or modular (Ulrich, 1995), and modular architectures can be further categorized into component swapping, component sharing, fabricate-to-fit, bus, and sectional modularity (Jiao et al., 2007). Modularity is a central topic for product architectures both for individual products and product families as it—to a large extent—determines the level of difficulty of making changes to the product portfolio. Modularity can be a means to reduce the dispositional effects in other life phases, e.g. by providing replaceable parts for service and maintenance or through module reuse across multiple product variants. According to Sanchez, modular product architectures are linked to several forms of strategic flexibility:

> - Ability to create greater product variety…
> - Ability to develop and introduce technologically upgraded products more quickly…
> - Greater speed to market…

- Lower design, production, distribution, and service costs…

(Sanchez, 2000, p. 614)

While products in a product family may all have an architecture, a product family architecture is said to exist only if the products in the product family share common elements across the product's architectures (Martin and Ishii, 2002). Commonality in the product family architecture is a characteristic that differentiates product family design from design of individual products, and the optimal result in product family architectures may be one that includes a mix of modular and integral features, if that allows for greater commonality and thus economies of scale (Jiao and Tseng, 2000; Sanchez, 2004). While commonality can be a virtue, compromises in product variant performance made to achieve commonality need to be taken into account to ensure that commonality provides net-value for the firm.

Harlou defined three levels of product architectures: *Assortment*, *family*, and *product* (2006)—illustrated in figure 3.7. The *assortment* architecture covers the product assortment of the firm with an emphasis on the future of the products—3–5 years into the future. Thus, it covers several product families and may include elements from multiple generations of product families. While the assortment architecture covers several product families, the *family* architecture covers a single product family and comprises the common elements, unique product variant elements, and future elements of the product architectures belonging to the product family. The product architecture is an instantiation of the family architecture—it covers a single product of the product family and includes only elements that are included in that particular product. Harlou's architecture hierarchy captures many aspects of product family planning: commonality through standard designs, variant creation through specific designs (design units), and a planning perspective for the product families through future standard designs and design units.

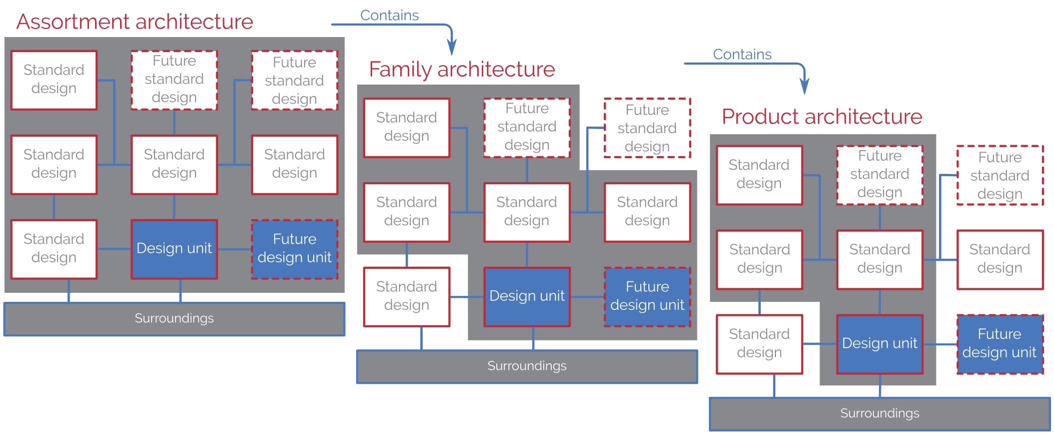


Figure 3.7: Harlou defined three hierarchical levels of architectures (Redrawn from (Harlou, 2006))

Contribution to this research Although multiple definitions exist for product architectures and those definitions are not in full agreement with each other, some elements remain constant across definitions: it is the organisation—on varying levels of abstraction—of the elements of a product. These definitions provide the context for architecture modelling: capturing the elements of the modelled system and their organisation. Andreasen et al. (2004) incorporate alignment into the architecture definition—an important factor to take into account during Product Technology Architecture development, where the development—through dispositional effects—determines the range of potential capabilities that derivative products can provide. Modularity and commonality are both widely used approaches aimed at obtaining cost reduction while offering product variety, but neither corresponds to an end goal to be sought after blindly. Optimal designs often include a mixture of modular and integral features and commonality must be reached through serious contemplation of the compromises made to achieve it. That architectures can be viewed at different hierarchical levels provides a broader perspective on product architecture that can be useful in developing Product Technology Architectures.

3.3.1 Product platforms

Product platforms have gained widespread use in industry in the last decades. The fundamental purpose of product platforms is to systematically organize reuse of a group of resources for a family of products. Sawhney (1998) describes platform thinking—which frames the central rationale for a product platform—as follows:

> Just as siblings in a family share a gene pool, a firm's offerings are often similar in the way they are designed, manufactured, branded, distributed, and promoted. This common heritage suggests that firms should manage their offerings as families with a common underlying logic, and not as portfolios of unrelated entities. This shared logic is the platform. Platform thinking is the process of identifying and exploiting the shared logic and structure in a firm's activities and offerings to achieve leveraged growth and variety.
>
> *Sawhney (1998, p. 54)*

The definition of a product platform in literature varies in terms of scope and contents. Meyer and Lehnerd (1997) defined a product platform as:

> a set of common components, modules, or parts from which a stream of derivative products can be efficiently developed and launched
>
> *Meyer and Lehnerd (1997, p. 7)*

Muffatto (1999, p. 145) provides a derived definition of a product platform as "a relatively large set of product components that are physically connected as a stable sub-assembly and are common to different final models". These definitions focus on physical components, while e.g. Simpson et al. (2001) define a product platform as: "the set of parameters (common parameters), features, and/or components that remain constant from product to product, within a given product family"(p. 3)—which corresponds to a much broader definition.

Harlou (2006) defines a platform in relation to the assortment, family, and product architecture discussed earlier and makes a clear distinction between existing and future elements in the product architecture:

> A platform is a structural description of a product assortment, product family or a product. A platform is an instance of an architecture that only includes existing standard designs and their interfaces, i.e. interfaces among the standard design, interfaces among standard designs and design unit and/or interfaces among standard designs and the surroundings.
>
> *Harlou (2006, p. 86)*

Depending on the definition and how strictly the definition is interpreted—e.g. Harlou's definition—a technology under development may or may not fit the definitions of a product platform as they do not form part of an existing standard design. But when technology development goals are to develop the foundation for a product platform, the development can be seen as part of the front-end of platform development. According to Meyer and Lehnerd (1997), Product Technologies are part of the common building blocks of a product platform—as illustrated in figure 3.8.They define technology as "the implementation of knowledge with the potential to be incorporated into a product or service" (Meyer and Lehnerd, 1997, p. 45) but do not provide a more specific definition of a *product technology*[1].

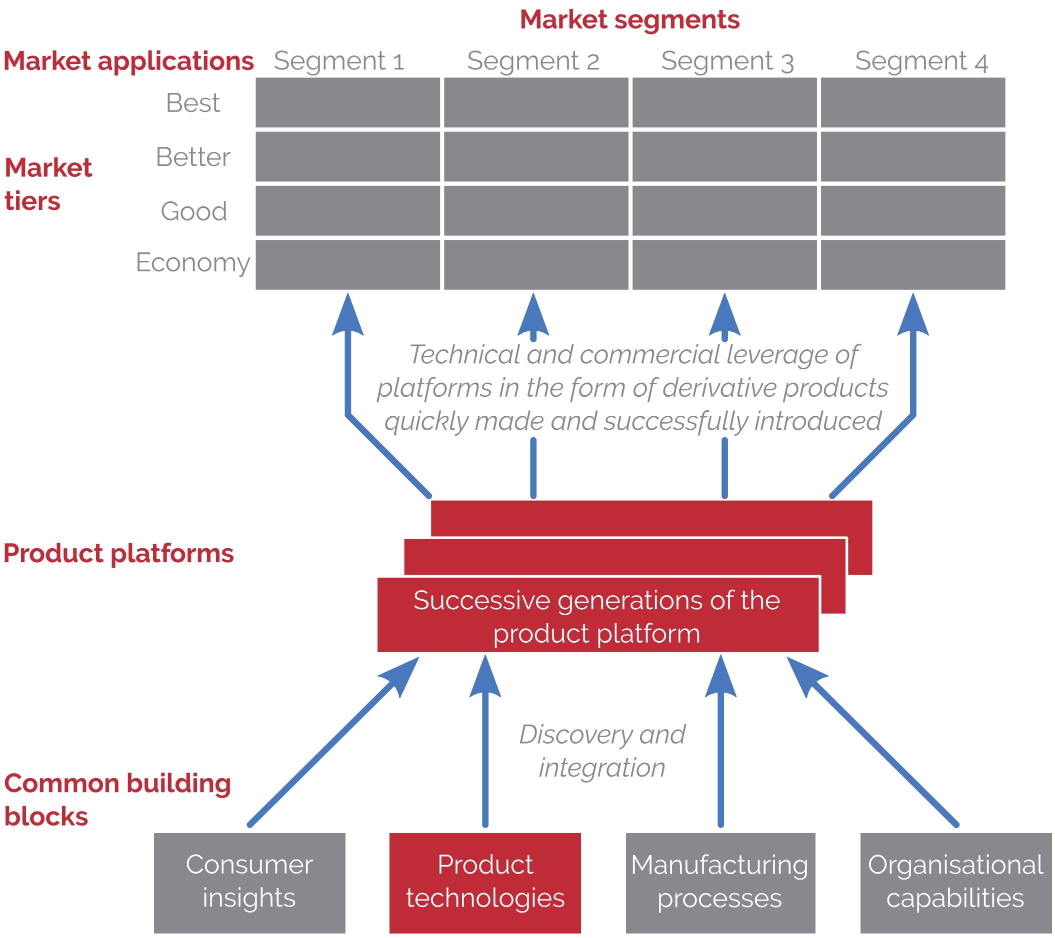


Figure 3.8: According to Meyer and Lehnerd (1997), the common building blocks of product platforms include Product Technologies (Redrawn from Meyer and Lehnerd (1997))

Contribution to this research Product platforms comprise that what is common across a family of products and thus directly supports commonality in the product family. What is included in the scope of a platform varies by the definition followed, but existing literature includes examples where Product Technologies are seen as part of the building blocks of a product platform. While the product platform descriptions in literature on commonality focus on sharing of physical, or at least discrete, elements across products, the phenomenon has potential in a technology development context.

[1]This definition is not far from the definition used in this thesis, to the extent that the two can be compared

3.3.2 Platforms in technology development

The available knowledge about a technical system being developed affects the foundation for making decisions regarding the development and activities within it (Mortensen et al., 2008). Sanchez (2000) defines three forms of knowledge for knowledge architectures: (1) know-how, (2) know-why, (3) know-what. *Know-what* knowledge—an understanding of the strategic options provided by a firm's technological know-how–enables the firm to envision new products based on what is possible through the use of technology and is based on *know-why* and *know-how* knowledge—theoretical and practical understanding, respectively, of how a technology works (Sanchez, 2000). These three forms of knowledge are essential for an organisation's ability to

1. maintain operations with current products and architectures
2. modify existing architectures or create new products and architectures
3. define concepts for new architectures and products.

According to Sanchez (2000) product and process architectures improve know-how learning, where know-why learning can be improved by researching new technologies and principles for future generations of products, and know-what learning can be improved by exploring new product concepts and architectures.

Sharing and supporting knowledge on technology is seen as important for technology intensive organisations (Nasiriyar and Jolly, 2007). A definition of a technology platform is proposed by Nasiriyar and Jolly (2007) that is highly focused on a technology platform as a collection of accumulated technological knowledge:

> "Technology platform is a set of distinctive technological competencies which is shared in different product families and applications. It is the result of firm's accumulated knowledge and experience and are exploited by searching new knowledge and leaving obsolete one in order to maintain their relative permanent leading edge feature. The platform technologies are reconfigured and reused inter-temporally in different core products and businesses and should be rejuvenated in order to respond the environmental and competitive changes. [sic]"
>
> *Nasiriyar and Jolly (2007, p. 13)*

However, the description of operational support in literature is limited. Levandowski et al. (2012) described the use of a central information database accessed through technology wikis, which were used to share information on technology knowledge within a firm. Described as a technology platform, the technology wiki—or technology platform portal—provides access for the firm's employees to a central portal with a categorized database containing short descriptions of technologies used within the firm and information on how to find out more (Corin-Stig, 2013; Johannesson, 2014)—as illustrated in figure 3.9.

The technology wiki is an approach to capture technology across the firm. The technology platform linked to the technology wiki is envisioned as a collection of methodologies, Product Technologies, production technologies, IT-based tools, and "other product and production matters of interest" (Johannesson, 2014, p. 126). Thus, the aim of the technology wiki is to support diffusion of technology know-how throughout the firm. In this vision of a

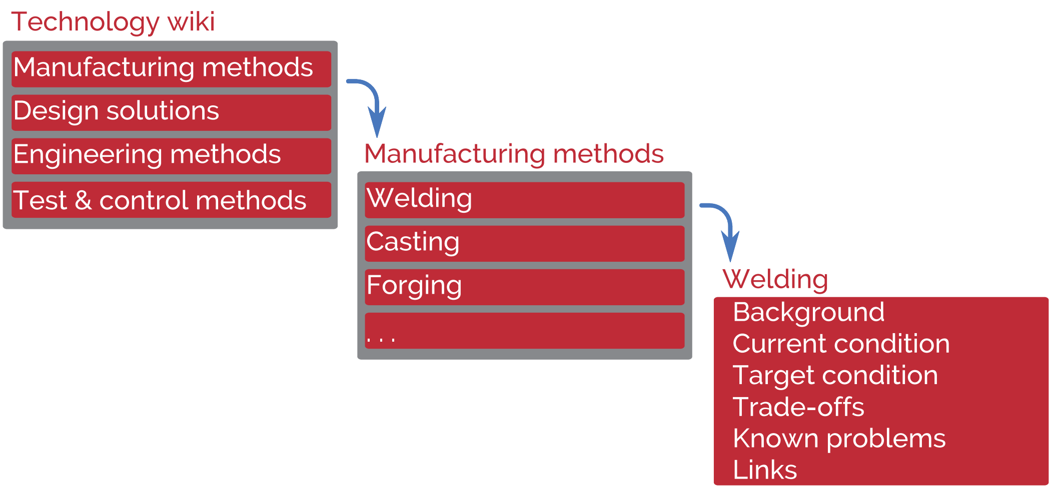


Figure 3.9: The technology wiki—or technology platform portal—provides a central information database on technologies used within a firm and where to obtain further information on those technologies. (Adapted from Levandowski et al. (2012)

technology platform the technologies of the firm are fed into product platforms at an adequate Technology Readiness Level and captured from existing systems and development activities in the technology platform.

Commonality in product platforms is a factor that is linked to reductions in e.g. lead-time, economies of scale, and R&D resource consumption (Harlou, 2006; Sanchez and Collins, 2001). By developing common design units, lower production costs and design efforts for derivative products can be achieved (Meyer and Lehnerd, 1997). Technology commonality—reuse of technological solutions—is an integral part of commonality in products, but also shows promising results on a technology platform level (Högman, 2011). On a technology platform level, the aim is to reuse technology knowledge at a more abstract level than in product platforms—the principles and both design and production technologies are reused but in new dimensions and new products.

Contribution to this research Knowledge about the products of the firm and their potential is essential for a firm's strategic flexibility—knowledge of Product Technologies can be seen as an essential part of this. Technology platforms have been defined in literature, but with a focus on existing technology competencies. Within technology development, new and emerging technology competencies can be expected to play a larger role than outside such a setting. While accumulated technology competencies certainly form a part of technology development, the existing definition fits poorly within this context. However, this provides precedence for systematic consideration of a technology platform. Operational support for technology platform development is scarce—if not non-existent. But support for systematic sharing of existing knowledge—including technology competencies—across a firm's business units has been implemented in industry. Results from that implementation indicates that technology platforms—sharing of technology competencies across multiple product families—can provide value in an industrial setting.

3.3.3 Product Architecture Modelling

Product architecture models aim to capture information and communicate a description of the product architecture. Engineering design literature contains a multitude of product architecture model descriptions (Eppinger and Browning, 2012; Harlou, 2006; Hölttä-Otto, 2005; Stone et al., 2000; Tiihonen et al., 1998). The models are often linked to different needs at different phases of development, there are differences in the intended application of the product architecture model and they provide a different perspective on the product.

3.3.3.1 Function modelling

Function modelling is rooted in the idea that the physical form of the product is meant to realize the functions that are expected of the product—therefore the models focus on the functions realized in the product and their interactions. Hubka and Eder's (1988) use of organs to represent function carriers within products is a central contribution to function modelling of products, and later models have carried on this perspective in modelling formalisms for product architectures (Bruun, 2015; Harlou, 2006; Kvist, 2009; Pahl and Beitz, 2007; Pedersen, 2010). The generic organ diagram defined by Harlou (2006) represents a function based modelling approach that provides an organ based view of a product architecture. Shown in figure 3.10, it presents the organisation of organs in a product architecture, the relations between the organs through interfaces, and supports describing multiple related product architectures through the inclusion of *optional* organs—that are not present in all architectures—*optional* interfaces, and organ variety—where the organs differ between architectures but are always present in some form. Interface definitions are the enablers of reuse and commonality in a product family—those components that are to be reused or common need to be compatible with the interfaces of those components that they will interact with.

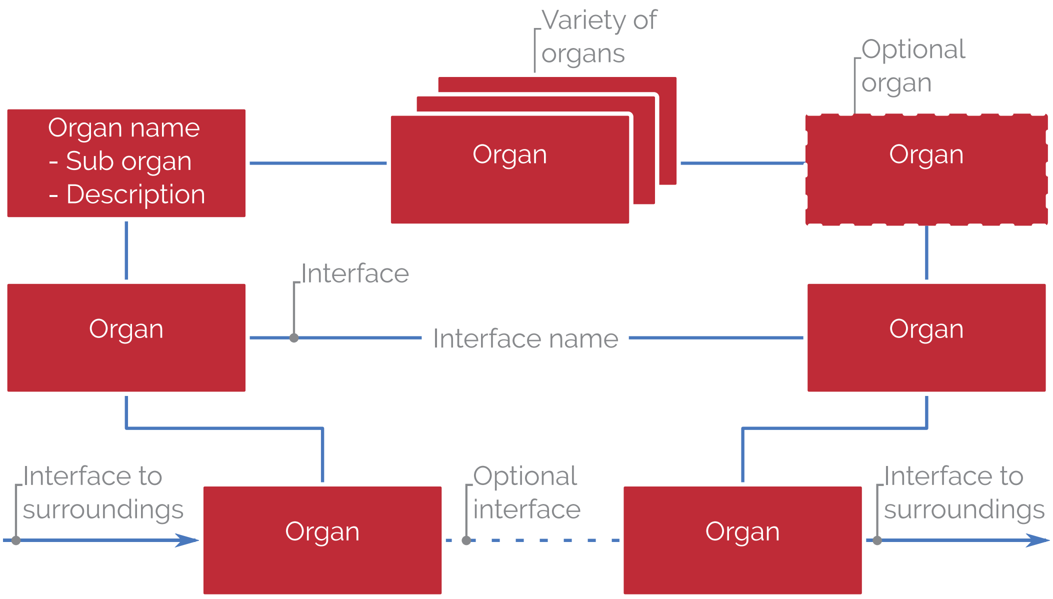


Figure 3.10: The generic organ diagram presents an organ bases description of the product architecture's structure and relations (Redrawn from Harlou (2006))

Function based models, such as the generic organ diagram, attempt to provide a mapping between the inputs to the system, through the internal functions of the system, to the outputs of the system in a way that the transformation process of the system can be read and mapped onto physical components. In a recent implementation of a function based modelling approach—the interface diagram—the models incorporated organs in the conceptual phases but transformed these into parts and components as the development progressed and physical parts defined (Bruun, 2015). Using organs provided a common basis for functional reasoning before physical parts had been conceived.

Contribution to this research Function modelling is a modelling approach based on describing how a system achieves the intended transformation. A focus on functions can provide a perspective that may be sufficiently devoid of physical realization to be utilized in a technology development context. Function based models can provide the necessary foundation for development of physical systems as organs capture the working principles within the system.

3.3.3.2 Component modularity focus

Several modelling approaches focus on supporting modular product architecture design. Design Structure Matrix (DSM) is a well known approach that focuses on various relations and modularity within the product architecture (Eppinger and Browning, 2012).

The elements of the product are identified—decomposed—through a function, structure, or network model of the product. These models can be function models as covered above, focused on physical components of the product, or network models focused on the interactions within the system (Bruun, 2015; Hölttä-Otto et al., 2014; Sosa et al., 2011). As modularity is in focus, encapsulation and entity relations within the architecture are emphasized—as can be seen in the network model shown in figure 3.11. Bruun (2015) models modularity explicitly within the model itself, but modularity modelling can also be achieved using additional modelling techniques.

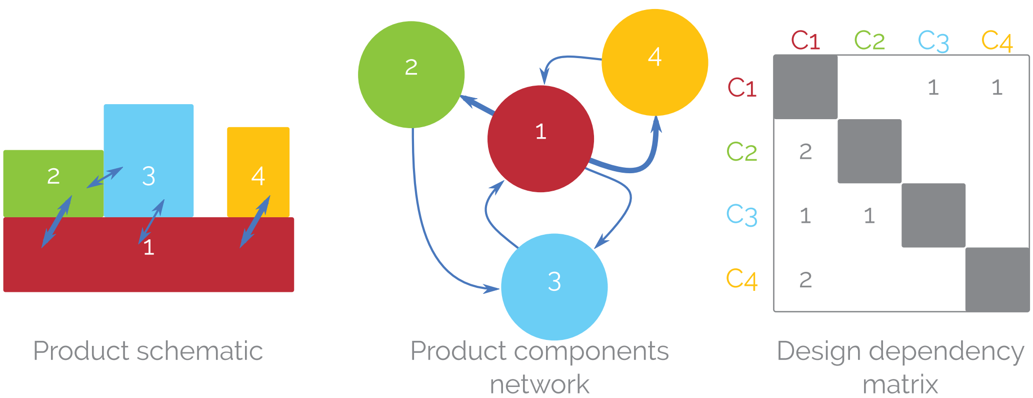


Figure 3.11: A network model emphasizes component relations and can be analysed using matrices (Adapted from Sosa et al. (2007))

Modelling approaches with a modularity focus sometimes utilize matrices in one form or another. In the DSM approach, a matrix is constructed on the basis of the system decomposition covered above. The matrix is filled out with information on e.g. which product components interact with each other. The significance of this interaction can be indicated with a value in each cell. This quantified interaction information can then be used for various computations run on the matrix. Algorithms can be run on the matrix to identify clusters that minimize external interfaces and maximize internal interfaces, which indicate prospective modules (Eppinger and Browning, 2012). However, module suggestions should be reviewed carefully by designers—module suggestions are only based on the information contained in the matrix on which the computations are run. Figure 3.12 shows a DSM of a system that has been clustered. One of the primary benefits of the matrix based methods is the ability to use software algorithms to identify modules in complex systems and fits well to complex systems where it is difficult to maintain an overview of the interactions in the system (Hölttä and Salonen, 2003).

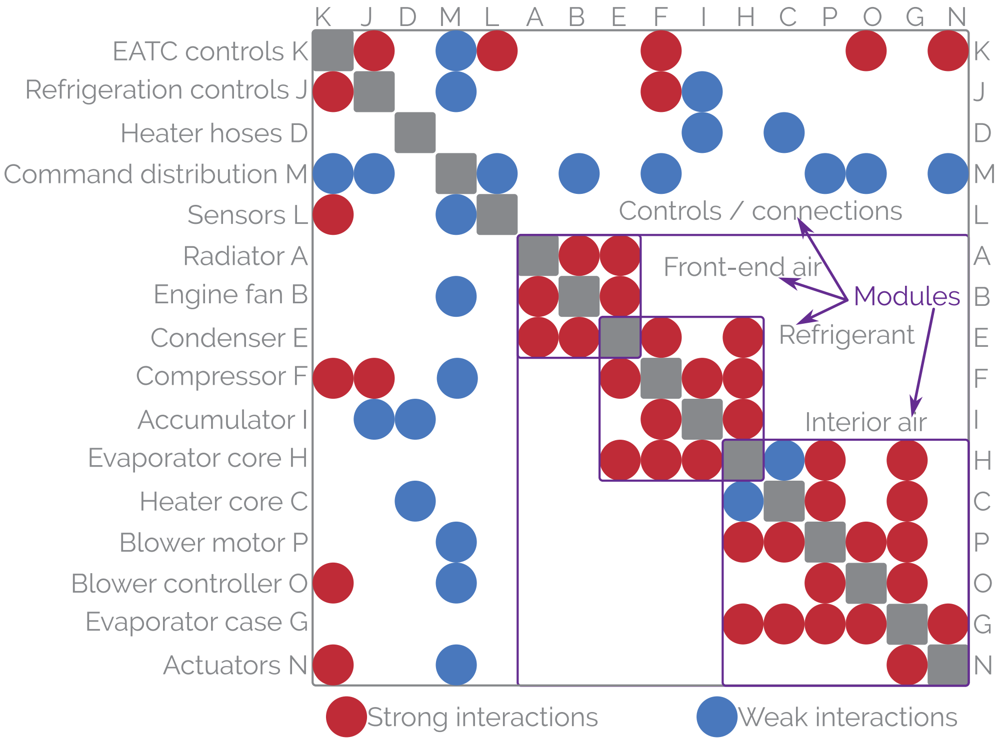


Figure 3.12: A clustered DSM for a climate control system (Redrawn from Eppinger and Browning (2012))

Contribution to this research While the usefulness of modularity as a modelling focus within Product Technology Architecture development is uncertain, modularity is a central topic in product architecture development and should not be overlooked. These modularity methods emphasize the importance of interfaces and identifying interactions between individual parts of any system. Matrix based methods facilitate the use of algorithms on complex systems and support identification of interactions may be a better fit for complex systems.

3.3.4 Product Family Modelling

Product family modelling deals with modelling multiple related product variants of a product family. Function modelling has led to the development of the Product Family Master Plan (PFMP), building on the Genetic Design Model System, but developed to model variety across product families (Harlou, 2006; Kvist, 2009; Mortensen, 1999). The PFMP presents a model of a product family that emphasizes commonality and supports modular architecture development. Harlou (2006) presents three views as central to the PFMP: the *customer* view, the *engineering* view, and the *part* view. In addition to these three views, Kvist (2009) proposed the addition of a view of critical design issues, the value chain and the total product offerings. The PFMP modelling formalism—shown in figure 3.13—presents a product family—within each of the three perspectives—in two structures: a *part-of* structure and a *kind-of* structure.

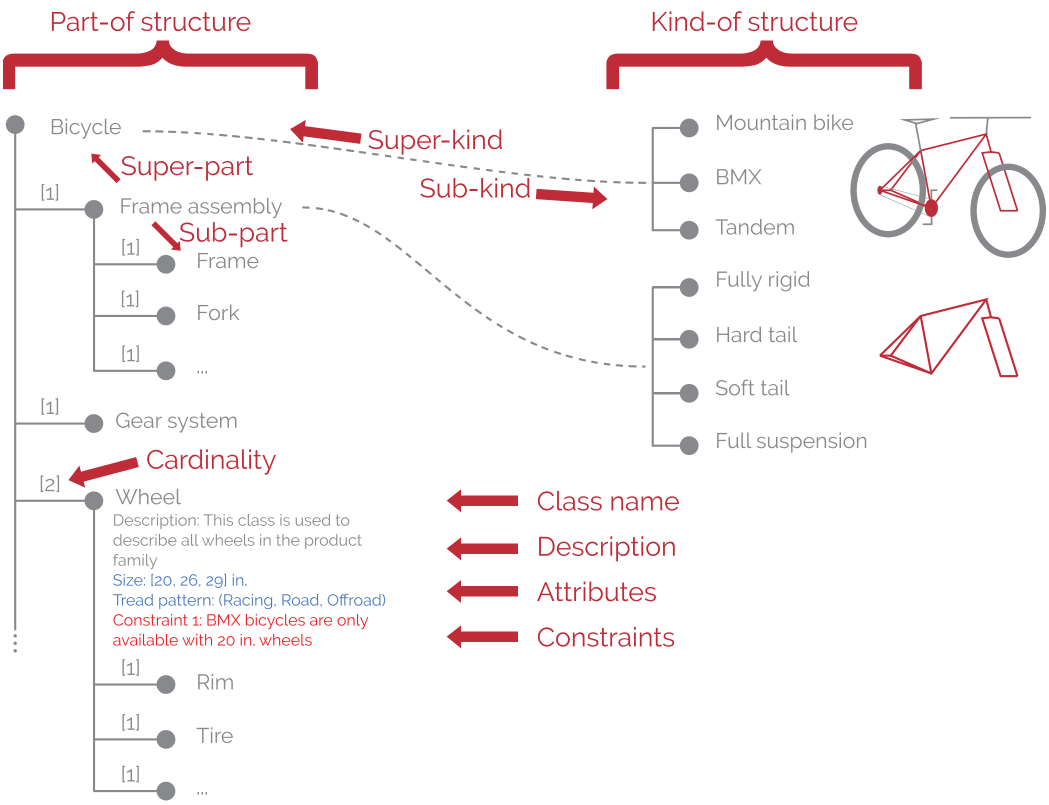


Figure 3.13: The PFMP contains two types of structures: *kind-of* and *part-of* and a clearly defined modelling formalism (Adapted from Kvist (2009))

The *part-of* structure describes the generic structure of the product family in terms of features, engineering principles, or parts, while the *kind-of* structure describes the variety of features, principles, and parts that are part of the product family. The *kind-of* structure is a sub-kind of the *part-of* structure and the *part-of* structure is furthermore hierarchically structured into super-parts and sub-parts. The cardinality of each part indicates how many instances of that part are included in a product instance derived from the product family. Individual features of the product family are described through classes—in accordance with object-oriented modelling—that define a class name, description, attributes, and constraints.

The three perspectives of the PFMP are causally linked as shown in figure 3.14. The engineering principles and parts represent how the product family realises the features and technical requirements described in the customer view—the causal links explicitly model this relationship. In the same way, the causal links show where the contents of the engineering and part views create value for the customer in the customer view.

The PFMP provides a modelling framework that is capable of providing an overview of the

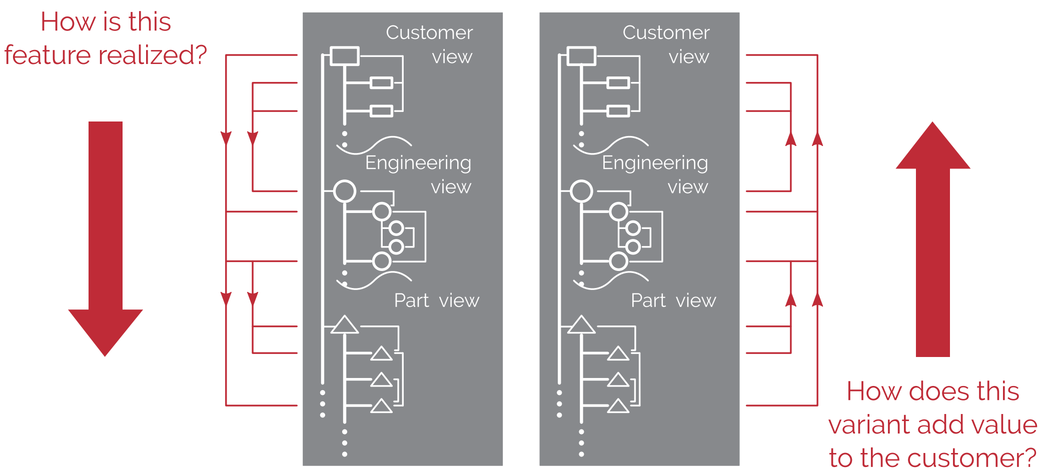


Figure 3.14: The three perspectives of the PFMP are causally linked—which indicates both feature realisation and value of variants (Re-drawn from Harlou (2006))

commonality—and variety—within the product family, while also covering details such as attributes and constraints—which are important when developing platform based product families.

The DSM approach has also been adapted for use within a multi-product context. The DSM-3D and DSM-variety add dimensions to the DSM in order to provide a matrix that covers multiple products—both shown in figure 3.15. Clustering algorithms can then be applied on multiple products simultaneously (Alizon et al., 2007; Hölttä and Salonen, 2003). However, reading the multidimensional DSMs becomes more difficult than with single product DSMs.

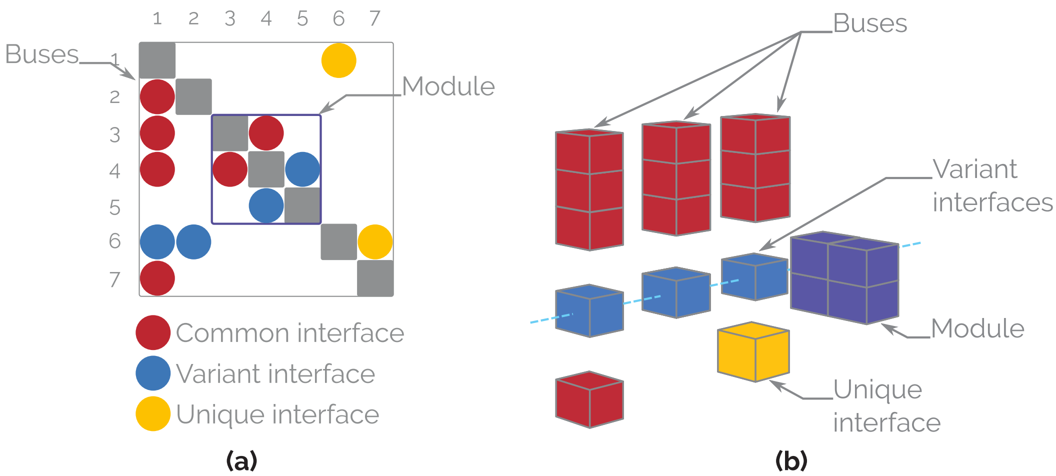


Figure 3.15: Two approaches for using DSMs for multiple products: (a) DSM-variety and (b) DSM-3D (Adapted from Eppinger and Browning (2012))

A comparison between figures 3.13 and 3.15 shows how there is a drastic difference in the way the approaches provide overview of a product family. While commonality and modularity can be read with relative ease in the multi-product DSMs, the hierarchical breakdown of the product family and the nature of commonality and variety among variants is much more visible in the PFMP. The strength of DSMs is also lost somewhat in a multi-product context—Hölttä and Salonen (2003) stated that as the intended use of the DSM method was to modularize single products, they did not scale well to the modelling of product families. However, as the modelling formalism of the PFMP is aimed at mature product platforms at a high level of detail and certainty of data, it is not certain how well it is suitable for implementation in a technology development context.

Contribution to this research The PFMP provides a means to model a product family that enables both an overview of the product family and information on the attributes and constraints related to product variants. The modelling approach furthermore shows the value of causal relations between technical principles and customer requirements. The comparison with multi-product DSMs shows the value of modelling the nature of variety and commonality in a way that is easily understood by the viewer.

3.4 Production architecture

There is not much literature on what a production architecture is—literature on production architecture tends to focus on production philosophy rather than architecture as discussed in this thesis (Jepsen, 2015). The previous discussion on product architecture can be viewed as covering production architecture to the extent that it can be viewed as a product or system. A recent PhD thesis from DTU provides a definition of a production architecture based on system architecture as:

> “Fundamental concepts or properties of a production system embodied in its elements, relationships, and in the principles of the system's design and evolution that address the requirements and constraints from its intended applications.”
>
> *Jepsen (2015, p. 50)*

Jepsen (2015, p. 50) also lists essential contents of a production architecture description. This listing covers the elements of the production system, their organisation and relations, the principles of the system's evolution over its life-cycle and the relation between the system's design and it's intended applications. Heavily based on system architecture definitions, this definition of a production architecture and the list of content to be covered, however, explicitly includes the system's evolution. This is to a large part to account for multiple roles that a production system may be expected to have as changes are made to the products to be produced by the production system—and is further influenced by Jepsen's focus on developing an approach to model configurable production systems that are roughly analogous to product families.

As the result of literature review on production system development and related literature, paper G presents the following categorized list of relevant factors that forms the requirements of what should be represented in a Production Architecture model during technology development:

Structural elements of a Production Architecture—what is it?

- The constituent elements, such as sub-systems, the equipment and workstations (Matt, 2008), and functions and structure, where the structure is the organisation of the physical elements and their relations (Hubka and Eder, 1988).

- Links from a production system's elements and functions to elements of the product architecture through dispositional effects (Olesen, 1992).
- Indication of the choice of production technology, as it is a key determinant in the achievable functionality of the production system and capital expenses required to implement the production system (Farooq and O'Brien, 2012; Skinner, 1985).

Functional elements of a Production Architecture—what can it do?

- Product flexibility, as it is the capability to produce new product variants economically (Jain et al., 2013), which is necessary when the product architecture description is not complete, although more flexibility is not necessarily better – the aim should be to obtain the right flexibility (Boyle et al., 2002; Matta et al., 2010).
- Volume flexibility, as it is the range of production volume within which the production system can profitably produce products and is especially important in new product introduction (Negahban et al., 2014).
- Processing and setup times, batch sizes, and the amount of partially produced goods within the production system, as these greatly affect the performance of the production system (Matt, 2008; Russell and Taylor III, 2011; Suh et al., 1998).
- Product differentiation points, as these affect product design as well as product and volume flexibility (Yang and Burns, 2003).
- Indication of obtainable quality, as quality is generally prioritized over flexibility and should be considered during production system development (Inman et al., 2013).

Expansions to the Production Architecture—what should it be able to do in the future?

- Production volume scaling, as moving from a laboratory setting to industrial production scale can require rigorous experiments on industrial production equipment to identify performance parameters and improve obtainable quality (Galagan et al., 2011; Taguchi et al., 2004b).
- Capabilities, as these can be expanded upon to enable delayed investment for capabilities that are not needed until later on – interfaces between sub-systems are central to facilitating capability expansion (Jain et al., 2013).

Contribution to this research The definition of a production architecture based on systems architecture shows the tight relations between a production architecture and a product architecture. The two phenomena are related, although their applications and goals are different—at least when the production architecture is seen from the perspective of a firm intending to produce its own products. But, naturally, a production architecture can for some firms be the product itself. This research, however, views the production architecture as distinct from the product architecture to emphasize their different roles from the perspective of a technology developing firm aiming to produce products based on a new technology. From this perspective, both lists covered here provide support for defining the content of a production architecture model within a technology development context.

3.4.1 Modelling production architecture

Modelling a production architecture can be viewed as the task of modelling the production system from an architecture point of view—analogous to the discussion above—or the task of modelling how the production system physically realises the products in the corresponding product architecture.

As an example of the latter perspective on Production Architecture modelling, Jiao et al. (2006) present the Generic Process Structure shown in figure 3.16, which is part of the process platform planning approach Zhang and Jiao (2013). While the term is different, the contents of the process platform planning approach are highly related to modelling Production Architectures.

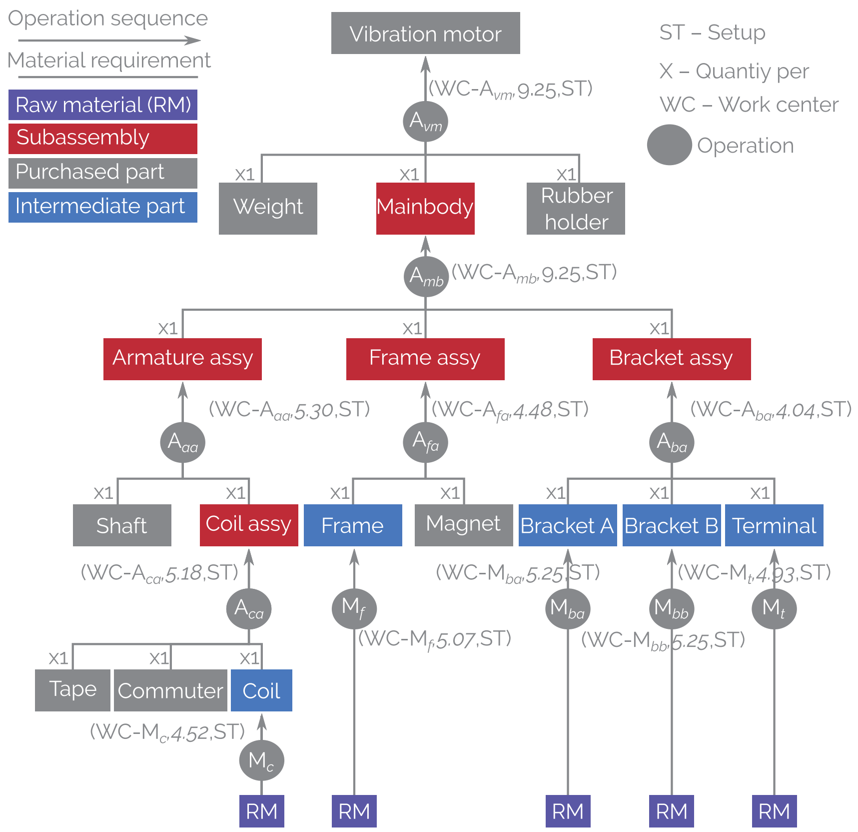


Figure 3.16: A generic process structure for a motor family (Redrawn from Jiao et al. (2006))

The Generic Process Structure links the production processes related to a class of products to their Bill-of-Materials. The model carries a description of the production operations, components, and sub-assemblies involved in the production of product variants from the product family. The tree structure in figure 3.16 includes all operations, components, and sub-assemblies to produce all product variants contained in the product family, although not all product variants require all elements in the tree structure. Product variants may require different process routings and process parameters. The variety parameters for a product variant for each operation are given by a parameter vector, which can be used in product configuration software to select the production resources for any given product variant that fulfil the set of planning rules associated with the process platform (Zhang et al., 2007).

The process platform-based production configuration approach facilitates the use of software algorithms to optimise routings but relies on data mining for optimisation and fits best to production in which assembly of two components involved in most operations (Zhang, 2007). Furthermore, the process platform planning approach implicitly assumes that the product family has been designed and may not be suitable for process planning in conjunction with product family development (Zhang and Jiao, 2013).

Contribution to this research The process platform-based production configuration approach provides a perspective of the production system in relation to a product family that focuses on the way operations lead to the production of product variants. While the process platform planning approach may not be suitable in conjunction with technology development, it provides a description of the value of linking product variants to a process platform. The production system—in this case represented by the process platform—exists to produce product variants from the associated product family and its contents are directly derived from the required operations to realise the product variants.

3.5 Conclusion on the theoretical basis

Technology development is characterised by a gradual clarification of uncertainties through development and testing. Suitable production capabilities can be critical in facilitating an investigation of obtainable product quality through prototypes and the feasibility of industrial volume production. Theory of Technical Systems, Theory of Domains and Genetic Design Model System represent the foundation of how a system is understood in this research. Many of the concepts and perspectives in the modelling approaches presented in chapter 5 build upon the concepts and perspectives of these theories. Nonetheless, while technology appears in and is discussed by these theories, a deviation is taken within the research reported in this thesis. Technology is not seen as belonging only to the activity domain as a transformation, as in these theories, but is—in the case of Product Technology—described within the organ domain. This is spawned from the perspective of the researcher that technology development—in the form of product technology development—is concerned not only with activities but also with developing the means of achieving functionality within a system.

Product architecture describes the aligned structure and relations of the elements of a product. Furthermore, a multi-product architecture—especially modular architectures—rely on strict interface definitions to facilitate reuse and stability within a multi-product architecture. Relating the theme of architectures to a technology, it is therefore natural to ask whether a Product Technology Architecture can be described with the same concepts. Products to be based on the technology that share Product Technologies may be viewed as having a shared Product Technology Architecture. This sharing may, however, not be as direct as in mature NPD. Limiting the scope of a Product Technology Architecture to Product Technologies may enable identication of a generic structure in a similar way as in mature product family architectures. Such a generic structure will, however, be on a more abstract level than in mature product family architecture—both due to greater uncertainties and to the greater potential for variation amongst potential product variants. The physical layout of parts is not necessarily the foundation for such a structure but common Product Technologies are, along with information on how they combine to provide the intended product functionality. For example, the particular geometries and dimensions of product variants to be derived from a Product Technology Architecture are not known—but they are also of lesser importance than in mature product family architectures. Reuse of Product Technologies lies in acquiring the ability to implement the Product Technologies in multiple products and is not dependent on part reuse—within a technology development context, parts can be expected to differ greatly between prototype variants. Interface definitions in a Product Technology Architecture cannot—for these reasons—be used in the same form as in mature product platforms. Previous descriptions of technology platform approaches in literature are, however, not focused on interfaces, but on facilitating sharing of technical capabilities within a firm. While no operational descriptions of a technology architecture are found in literature, there is precedence for sharing of technology.

The PFMP is the foundation on which modelling within a multi-product development context is built as it provides a systematic overview of commonalities and variety within a product family—although it cannot be directly adopted in a technology development context. The causal relations between domains—inherited from the Genetic Design Model System—are also central in the form of entity relational modelling that is applied in the architecture modelling frameworks presented in the chapter 5.

Production Architecture modelling from a systems perspective is not extensively dealt with in literature—existing literature on Production Architecture deals with specific design philosophies rather than modelling approaches. Recent literature, however, supports a systems perspective on Production Architectures and that architecture modelling approaches can provide a foundation for Production Architecture modelling. Literature on production systems provides insight into what a Production Architecture model should contain. The process platform planning approach emphasizes the existential relationship between a product architecture and Production Architecture—the production system exists to produce the products. Although relying on quantified historical data for optimization of a process platform—which is scarce in a technology development context—the approach provides a perspective on modelling the generic process structure in relation to the product.

The next chapter describes the case background and progress in the most relevant tasks of the case project, before the research results are presented in chapter 5.

CHAPTER 4

Case study

Technology push is a solution looking for a problem. It is much more difficult than finding a solution to a problem.

—A Philips Design executive on technology push projects

This chapter describes the DEAP project case. The case background and organisation is described in section 4.1, followed by a short introduction to Dielectric Electro-Active Polymer (DEAP) technology and an account of the situation at the outset of the project. Section 4.2 describes the platform development in the DEAP project case by providing an overview of the tasks involved, the researcher's role in the platform development, and a concise account of the development results in the project. Section 4.3 then concludes this chapter by describing the production development in the DEAP project case in a similar way.

4.1 Case description

This research was performed within a Public-Private-Partnership project (Hansen, 2013) involving industrial and academic collaborators. All in all, thirteen different organizations—three universities, a public funding organisation, and nine private firms—were directly involved in the project with more than ninety people comprising the human resource base. The project ran for four years with a total budget of approximately one hundred million DKK.

4.1.1 Background and organisation

The project, funded by Innovation Fund Denmark (IFD), was centred around the development of a DEAP technology based on utilizing Maxwell pressure as a result of a high electric field across a laminated DEAP film that can be configured in a variety of ways to construct actuators, generators, and sensors—see section 4.1.1.2 for a short introduction to DEAP technology. The aim of the DEAP project was to achieve a commercialization of a wide variety of DEAP-based products through concurrent development of the base technology, production processes, DEAP components, high voltage drivers for DEAP components, and products incorporating

DEAP components. The project was organized into ten Work Packages numbered zero through nine (Work Packages 0–9)—an overview of which can be seen in figure 4.1—where each work package focused on a particular task within the project. The Work Packages teams comprised either participants from a single organisation or from multiple organisations. In figure 4.1 the abbreviations beneath the Work Package name indicate the organisations participating in that Work Package.

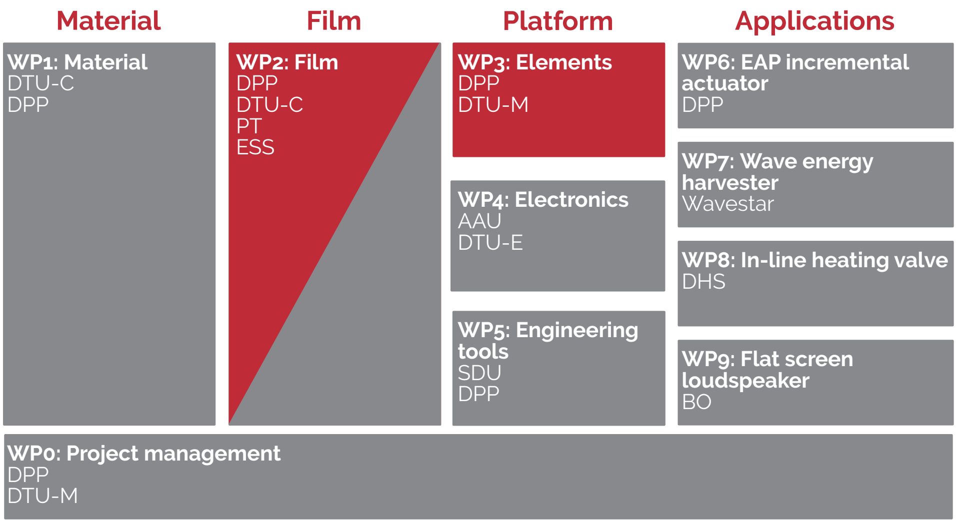


Figure 4.1: The DEAP project was organised in work packages (Work Package 0–9). The majority of the research focused on Work Package 3, but Work Package 2 was also supported. (Adapted from project documentation)

4.1.1.1 Research focus within case

The focus of this research was on following and supporting a central stakeholder, Danfoss PolyPower, that had been developing the DEAP technology for several years and who aimed at developing the foundation for a broad product portfolio based on DEAP technology by adopting an architecture based approach. Within the DEAP project, Danfoss PolyPower had the role of developing DEAP components (Work Package 3) and production processes (Work Package 2) and to deliver DEAP components to collaborators for use in prototypes incorporating DEAP technology in four applications; an incremental actuator, a wave energy harvesting machine, a heating valve, and a loudspeaker. All application prototypes were developed from the ground up within the project. All prototypes except for the incremental actuator—which was developed by Danfoss PolyPower as a proof-of-principle—were based on existing knowledge and products within the respective collaborating firms, but the DEAP technology required new designs to investigate and utilize its performance potential.

4.1.1.2 DEAP technology

DEAP technology is based on Maxwell's pressure—a phenomenon that induces attraction between two electrodes when voltage is applied. The Danfoss PolyPower DEAP laminate shown in figure 4.2 comprises two DEAP films that have been laminated together. Each film is composed of a silicone dielectric with a corrugated pattern on one side of the film,

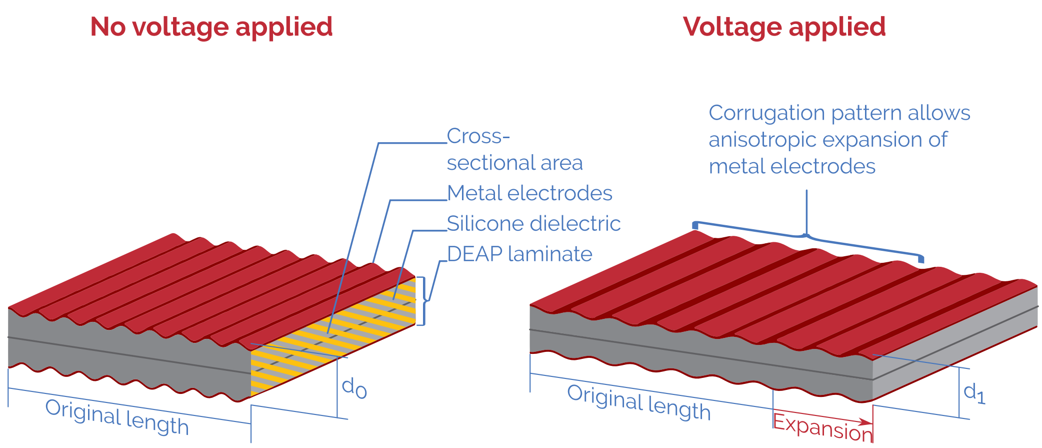


Figure 4.2: A DEAP laminate becomes longer and thinner when high voltage is applied across the electrodes

onto which a metal electrode is deposited. The corrugation pattern allows an anisotropic expansion of the DEAP laminate without the metal electrode breaking—as the thin metal experiences bending the actual elastic forces on the metal electrode are reduced dramatically. When voltage is applied to an unconstrained DEAP laminate, the DEAP laminate decreases in thickness due to the Maxwell pressure and due to the silicone dielectric's incompressibility it's length increases perpendicular to the corrugation pattern in proportion to the change in thickness—as seen in figure 4.2. When the expansion of the DEAP laminate is constrained, the DEAP laminate exerts a force against the constraint that is proportional to the cross sectional area of the DEAP laminate that is parallel to the corrugation—perpendicular to the expansion direction.

The expansion of the DEAP laminate is governed by the electrostatic pressure inside the DEAP laminate. The electrostatic pressure for a planar DEAP laminate is given by Tryson et al. (2009):

$$\sigma = \varepsilon_0 \varepsilon_r (E)^2 \tag{4.1}$$

where

σ = The electrostatic pressure

$\varepsilon_0 \approx 8.854\ldots \times 10^{-12} \mathrm{F} \cdot \mathrm{m}^{-1}$ is the permittivity in a vacuum

$\varepsilon_r \approx 3.1$ (for the DEAP material) is the relative permittivity of the dielectric material

$E \approx 50 \frac{\mathrm{V}}{\mu\mathrm{m}}$ is the electric field across the electrodes

The force and stroke of a DEAP transducer is determined by the force-stroke equilibrium of the transducer at the applied voltage:

$$S = \frac{L_0}{Y_{DEAP} \times A} \cdot \varepsilon_0 \varepsilon_r (E)^2 \cdot A - F_{load} \tag{4.2}$$

Where:

$$
\begin{aligned}
S &= \text{The stroke of the transducer} \\
L_0 &= \text{The inital length of the transducer} \\
Y_{DEAP} &= \text{The Youngs modulus of the DEAP material} \\
A &= \text{The cross sectional area of the transducer} \\
F_{load} &= \text{The applied load against the stroke of the transducer}
\end{aligned}
$$

From equation 4.2 it can be seen that the stroke (or force) provided by the transducer increases quadratic proportionally with the voltage applied, but there are limits to how high the applied voltage can be—if exceeded, a breakdown in the material occurs that destroys the electrode and dielectric around the area where the breakdown occurs. Dimensioning a DEAP transducer with a given set of material parameters is therefore a question of balancing the DEAP laminate thickness, the voltage applied, and the cross sectional area of the DEAP transducer. With the Danfoss PolyPower DEAP laminate used in the DEAP project, the applied electric field was around $50\frac{V}{\mu m}$ (up to 2–2.5kV)—which required expensive high-performance electrical components to drive the transducers. Developing a material that would allow a reduction of the applied voltage while achieving high performance from DEAP transducer was a key goal in Work Package 1.

Some of the key Product Technologies in a DEAP transducer are the mechanical interface to the DEAP laminate, the electrical interface to the DEAP laminate, the DEAP laminate itself, and the DEAP transducer basic structure—which can take many forms depending on the design. The key challenge with the mechanical interface is to achieve a robust connection between the elastic DEAP laminate and a rigid part that can be used for mechanical connections with external systems. The key challenge with the electrical interface is achieving a low resistance connection to the electrodes that can be sustained while the DEAP laminate stretches during activation. The key challenge with the DEAP laminate is to achieve the necessary force and stroke performance with voltage requirements that do not exceed the dielectric silicone's electric break-down voltage. The key challenge with the DEAP basic structure is to achieve a structure that provides the required performance with a sufficient lifetime. All the aforementioned challenges are linked to the morphing nature of the DEAP laminate, the high voltage required to achieve the required performance, and to developing Product Technologies that can be produced reliably with the required transducer quality.

4.1.1.3 Situation at the outset of the project

Although development of the DEAP technology had been in progress in Danfoss PolyPower for several years preceding the DEAP project and promising results had been delivered (Tryson et al., 2009), the technological maturity was at a low level at the outset of the project. Development of a foundation for a broad product portfolio required development of new technical solutions for almost all facets of the DEAP technology: transducer structure, mechanical and electrical interfaces, encapsulation, lamination, and production processes. The task at hand was to develop the technological foundation for a product portfolio where historical product data to base product development on was practically non-existent and the technological know-how needed to be expanded along the way. This task was fraught with uncertainties, as neither the products, production processes, base technology, nor the applications, were fully defined.

4.2 The platform development in the DEAP case

There were four main tasks in Work Package 3 that related to the development of a DEAP transducer platform. Each of the four main tasks was broken into subtasks—the project plan for the main tasks and their sub-tasks is shown in figure 4.3. *Element specifications* comprised identifying application requirements, developing DEAP transducer concepts and mapping the identified application requirements to the DEAP transducer concepts in a high-level architecture as the basis for the further development of the platform. *Platform technology* development comprised the development of principal technology solutions—the Product Technologies. These Product Technologies provided the building blocks from which a diverse set of DEAP transducers could be constructed and represented key challenges to be overcome to enable the construction of DEAP transducers. *Platform components* development aimed at developing DEAP transducers—using the Product Technologies—that could fulfil the identified application requirements and be implemented in Technology Prototypes in the DEAP project. *Design-build-test demonstrators* comprised the activities related to constructing DEAP transducers to be implemented in the Technology Prototypes.

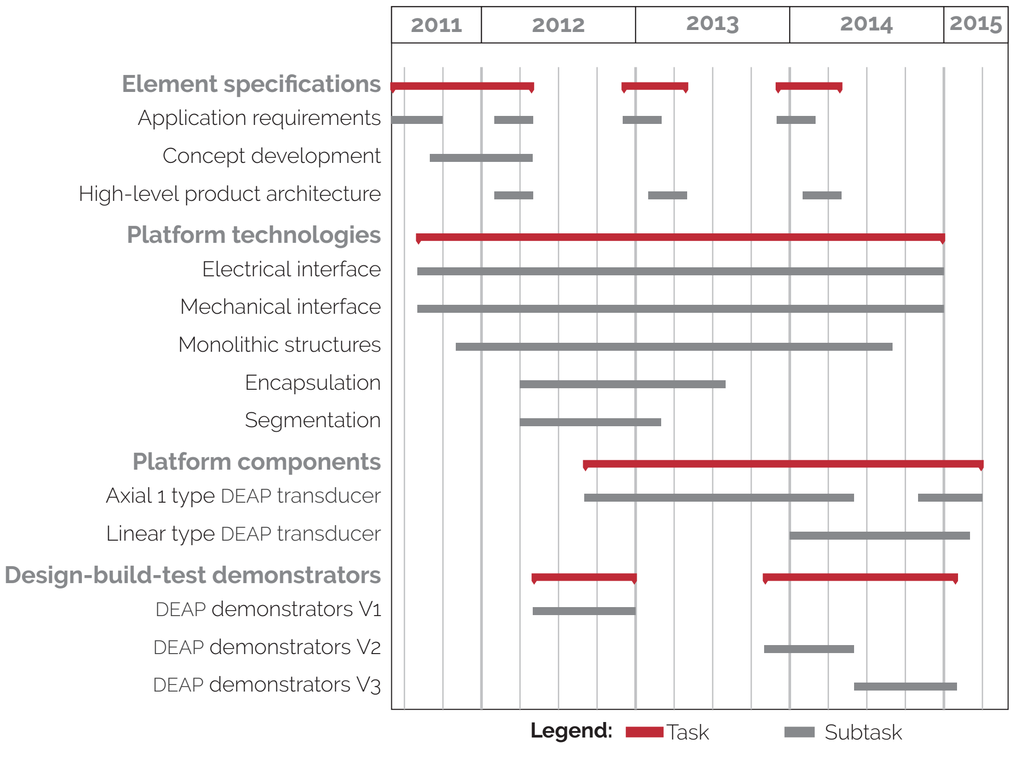


Figure 4.3: The platform development process in the DEAP case had four main tasks

Some tasks represented challenges in developing Product Technologies and required subtasks to be revisited over a long period—for the *electrical interface* this was due to efforts to iteratively improve DEAP transducer's electrical interface robustness and electrical performance while *monolithic structures* required resources outside of the original Work Package 3 team.

The research was performed through active participation in the development activities as listed in table 4.1. The Product Technology Architecture modelling framework—described in section 5.2—was the primary support implemented as part of this research in the platform development Work Package. The results of the development tasks are presented in the following text.

Table 4.1: Participation in platform development tasks during the research

Task	Participation during research
Element specifications:	Participation in all sub-tasks
Platform technologies:	Participation in platform technology planning and overview activities
Platform components:	Participation in task with Work Package 3 project leader, defining production architecture for components, component definition, and analysis of prototype variant impact on resources.
Design-build-test demonstrators:	Participation in task with Work Package 3 project leader and participation in a number of application Work Package meetings.

The results of Element specifications development included an analysis of the identified application requirements that provided an overview of the required performance for DEAP transducers, transducer concepts fulfilling the identified application requirements, and a high-level architecture for the DEAP transducer platform. The identified application requirements forming the foundation for the specification of transducers represented a wide range of requirements—as can be seen in figure 4.4—which was one of the reasons for adopting a platform approach as it was considered uncertain what applications would prove most promising for commercialization of the DEAP technology. A roadmap for development of the required Product Technologies and transducer prototypes for use within the project was made to plan and prioritize development tasks.

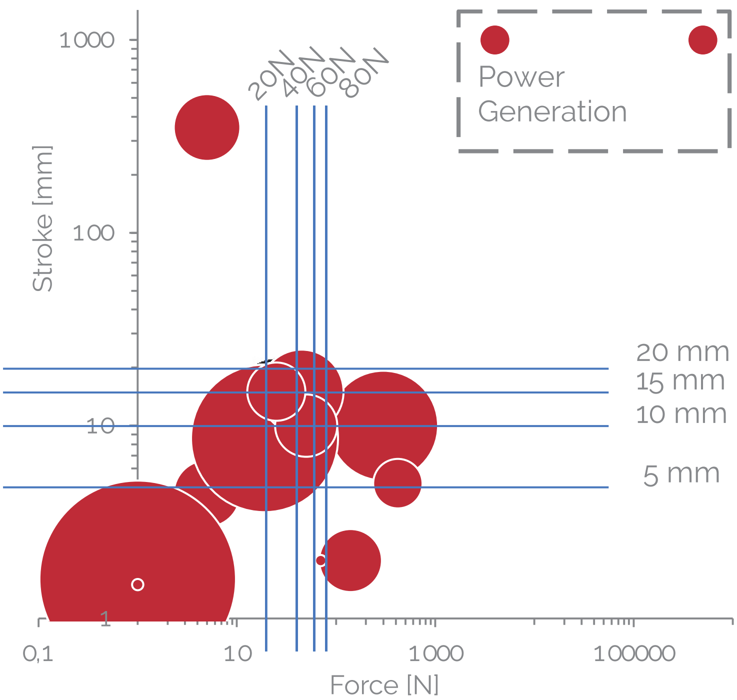


Figure 4.4: The identified stroke, force and frequency requirements varied greatly across applications. The size of each data point indicates the magnitude of the frequency requirements, which ranged from 0.1 to 3500 Hz.

The development of Product Technologies within the platform scope resulted in the successful development of one pure electrical interface alternative, one pure mechanical interface alternative, one hybrid electrical and mechanical interface alternative, two monolithic structure alternatives, two encapsulation alternatives and two segmentation alternatives. Figure 4.5 shows an overview of the developed Product Technologies.

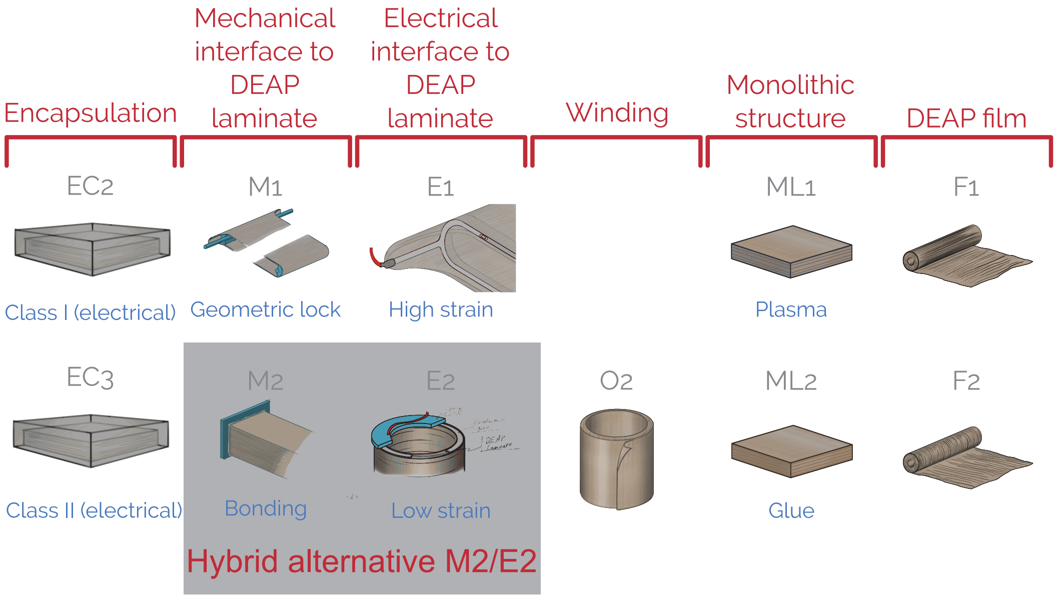
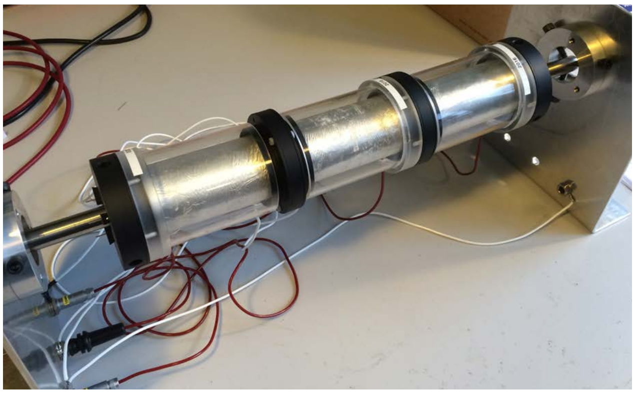


Figure 4.5: An overview of the Product Technologies that were developed within the DEAP project

While several DEAP transducer concepts were developed and included in the conceptual product platform, it was decided to focus development on two promising transducer concepts for further development during the DEAP project: The *Axial 1* and *Linear* type transducers shown in figure 4.6. Both transducer types were developed to a Technology Readiness Level 3 in the project.

DEAP transducers were designed, constructed, and integrated into Technology Prototypes in the application Work Packages—as illustrated in figure 4.6. The Technology Prototypes varied greatly in design and nature and as a result, the DEAP transducers also varied considerably. Some of the *Axial 1* transducer variants produced are shown in figure 4.7. Some reuse in tooling was achieved to reduce resource use in the DEAP project but the main reuse was on a non-physical level—the Product Technologies and design principles were common across Work Packages 6, 8, and 9.



(a) Photo: Rahimullah Sarban

(b) Photo: Emmanouil Dimopoulos

Figure 4.6: Two transducer types were developed in the DEAP project: Axial 1 (a) and Linear (b)—both shown in Technology Prototypes

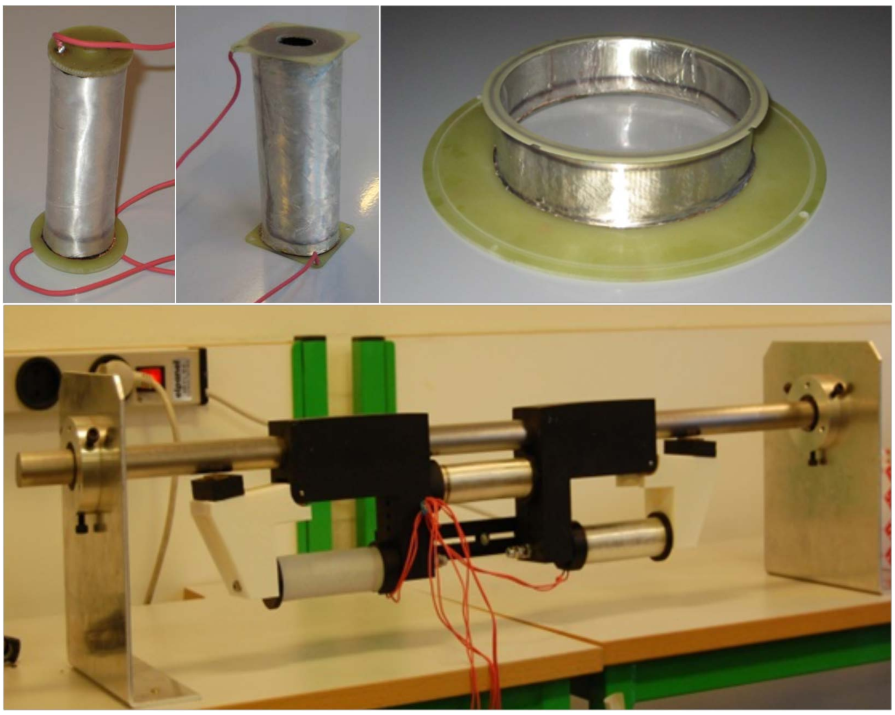


Figure 4.7: Four Axial 1 variants that were designed and produced in the DEAP project (Photos: Rahimullah Sarban)

4.3 Production development in the DEAP case

In Work Package 2—responsible for production development—many of the tasks were distributed over a large portion of the development project as can be seen in figure 4.8. Developing the production process was a complex and challenging task and many of the tasks were highly interrelated. The challenges were both directly related to the production development itself, and to progress in Work Package 1—where new versions of the base material were developed.

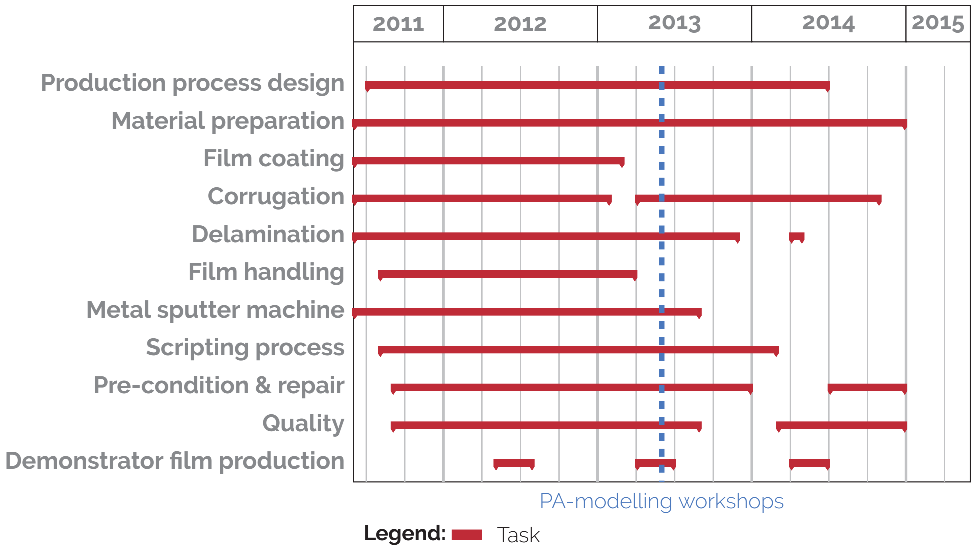
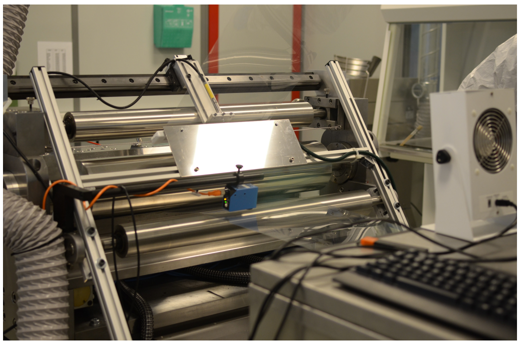


Figure 4.8: The production development process in the DEAP case

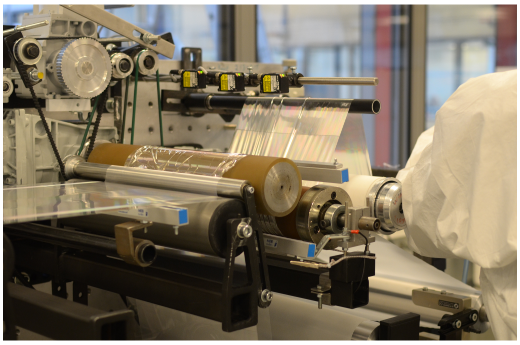
The production development was a resource heavy Work Package in terms of investments needed to implement the results of the tasks in the Work Package. Around the mid-point of the DEAP project the Engineering Design and Product Development research group were approached with a request to support identification and communication of the Production Architecture before decisions were made on implementation of production capability expansions.

The research in Work Package 2 was performed with much less involvement than in Work Package 3. The researchers involvement was limited to activities related to gathering requirements for, developing, implementing, and evaluating a support in the form of Production Architecture model—described in section 5.3.1. In figure 4.8 a vertical line indicates when active participation was initiated on behalf of the researcher through workshops related to the development and implementation of the support in the Work Package. For the majority of the DEAP project the Work Package was followed only intermittently through common meetings in conjunction with Work Package 3 and during project symposiums—which were held four times during the DEAP project with participation of almost all active project members. The following text presents the main results from the Work Package in summarized form.

Several areas of DEAP laminate production were improved through the production development. Material preparation processes were improved through new equipment and new processes. A new film coating process was implemented, which included improvements in both capacity and obtainable quality in the production—figure 4.9a shows the slot-die coater implemented in the DEAP project. De-lamination and lamination was improved although combining the two processes—which was a sub-goal meant to improve capacity—was not achieved. Practically eliminating wrinkles in these processes—see figure 4.9b—which was a critical cause for quality issues before the DEAP project, was a major benefit of the de-lamination and lamination process improvements. Improvements in the metallization process of DEAP film were achieved but not implemented in Danfoss PolyPower's production.



(a) Implementing a slot-die coater was part of the improvements to the coating process



(b) Wrinkles caused quality issues before process development practically eliminated them

Figure 4.9: New equipment and process development improved production quality in the DEAP project

Several parameters that affect obtainable quality were identified and considerable effort was laid into improving production quality. The production of improved DEAP laminate was successful on many accounts in the production process development but challenges in achieving improved material performance meant that meeting DEAP laminate performance goals was not possible.

4.3.1 Summary of case description

The DEAP project was a complex project involving multiple stakeholders, whether judged by the number of organisations involved—thirteen—the number of individuals—over ninety—or the number of sub-projects represented by the nine Work Packages. All three perspectives of technology development were accounted for in the DEAP project—use technology development in Work Packages 6–9, Product Technology development in Work Packages 3–5 (and essentially in Work Package 1 as well), and production technology development in Work Package 2.

The research focus was mostly on Product Technology development with extensive participation in Work Package 3, but production technology development in Work Package 2 was also supported—although with participation to a much lesser degree. Product Technology development resulted in the development of multiple Product Technology alternatives that were utilized in the DEAP project to construct multiple iterations and variants of prototypes representing two transducer types: Axial 1 and Linear type transducer prototypes. Production technology development succeeded in improving the production process. This included implementation of new equipment and improved production quality for the majority of processes involved but limitations in material performance limited achievable performance.

The results of the research within the DEAP project, including activities and challenges related to technology development and the development and implementation of architecture modelling frameworks in Work Packages 2 and 3 are presented in the following chapter.

CHAPTER 5

Research and results

There is nothing like looking, if you want to find something ... You certainly usually find something, if you look, but it is not always quite the something you were after.

—J.R.R. Tolkien, *The Hobbit,* (1937, chapter IV)

The results presented here comprise summaries of results included in the appended papers that have either been published or submitted during the research project—supplemented by results from the interviews and through participation in the case project. This chapter summarizes each paper's contribution to this research and my reflections on the contributions to this research.

5.1 Results related to RQ1

The results presented in this section stem from interviews performed during the research project, participation in the DEAP project, and from research on application Work Packages. Part of this research has been published in the following papers:

Paper A	
Title:	*Tasks and challenges in prototype development with novel technology—an empirical study*
Authors:	Poul Martin Ravn, Tómas Vignir Guðlaugsson and Niels Henrik Mortensen
Conference:	International Conference on Engineering Design 2015 (ICED 2015)
Research Question:	RQ1
Status:	Published

Paper B	
Title:	*A multi-layered approach to product architecture modelling—Applied to technology prototypes*
Authors:	Poul Martin Ravn, Tómas Vignir Guðlaugsson and Niels Henrik Mortensen
Journal:	Concurrent Engineering: Research and Applications
Research Question:	RQ1
Status:	Published (OnlineFirst)

In section 1.3.1, RQ 1 was stated as follows:

> **Research Question 1** How do the technology development activities and context during simultaneous product technology and production development affect architecture modelling in terms of what to model, what the model focus should be, and what goals should be supported by the models?

5.1.1 A broad context for technology development

Technology prototypes Although the interest of potential customers for getting involved with technology development—integrating novel technology into their products at an early technology development stage—varies, all interviewees emphasized the importance of the availability of functioning test samples to investigate. A dependable prototype that *just works* is—in this regard—of tremendous importance. Even when a firm is interested in integrating novel technology into a product under development, the firm expects a robust functioning prototype that enables the firm to focus their efforts on the integration of the technology into their products—not on troubleshooting faulty prototypes. Such prototypes need not necessarily contain all functionalities of the envisioned products or the full performance, but it needs to provide indications of the functionality and performance of the new technology in the potential customer's products. Potential customers are often willing to construct Technology Prototypes that have a different scale than their products, to investigate the performance of the new technology. However, there need to be indications in place that the technology developing firm has the capability to develop and produce products based on the new technology that fulfil the requirements of the customer concerning performance, quality, and production quantity.

Get products on the market In many cases—e.g. when the new technology represents a secondary system in the potential customer's product—there is no inherent value in introducing a new technology. The introduction of a new technology interferes with the existing product architecture and requires substantial benefits to warrant the disruption of the product architecture. For future products, the disruption of product architectures may not be relevant, but the customer has a solid experience with a particular solution and substantial benefits may be needed to warrant the risk of integrating new technology lacking proven performance in the field. However, if a new technology has been proven in commercial products—even if these are different than those of the potential customer—there is much more willingness to investigate the merits of the new technology. In such cases, the ability of the technology development firm to develop and produce products based on the technology to the level of quality required to be commercialized and produced in large quantities has been proven—which considerably reduces the risk of the potential customer. While some firms rely on in-house technology development and collaboration with technology developing firms to stay competitive, other firms are more risk averse and prefer to focus on acquiring and integrating proved technologies. The risk behaviour of firms varies greatly—both between individual firms and depending on the industry.

Demonstrate uniqueness Three market entry strategies for new technologies were discussed by the interviewees: Direct replacement, improved performance in an existing application through unique capabilities of the technology, and a fundamentally new application.

Entering the market in a fundamentally new application is the most difficult as it requires identification of an application that cannot be solved using existing technologies. To be a replacement actuator, the performance, the price, or both need to be better—preferably by a considerable margin—as there is a proven solution in place that needs to be beaten. While price is a rather generic parameter—it can be directly compared between solutions fulfilling the requirements—performance can be a more flexible parameter. Demonstrating unique capabilities provides an edge against competing technologies, but there is a catch—the unique capabilities must not be reproducible using current technologies in a simple way. An example mentioned by several interviewees is integrated positioning sensing. While no actuator technology on the market provides integrated—as part of the core technology—position sensing, it is easily added by integrating an encoder in the final design. As this is an easy and well known solution, integrated position sensing capabilities are of little value on their own—regardless of how unique they may be. To support commercialization, it is therefore important to identify the truly unique capabilities of the new technology and where these capabilities provide value. This may often not become clear without in-depth understanding of the applications of the customers—what provides value in their products—and as tacit needs may be fulfilled by a unique capability of a new technology, these may need to be uncovered through exploration of the use of the technology in the customer's application.

Develop critical production capabilities The importance of dependable prototypes was emphasized with regards to customer testing of new technology. Proving the capability to obtain the required product quality on a relevant scale—on equipment capable of industrial scale quantities—was also emphasized. Its importance is also focused on the firm itself—making sure that products with the functionality and quality being delivered to potential customers for testing can be produced on industrial scale equipment—to ensure that they can be produced profitably at a scale that is representative for commercial production. However, as implementing production capabilities is capital intensive, this can be limited to key processes and critical parts of the product being developed—parts that are analogous to parts being produced elsewhere in large quantities do not warrant implementation of capital intensive investments. Implementing these production capabilities is also part of providing evidence—towards potential customers—that the technology developing firm has the capability to start commercial production with the required product quality.

5.1.2 Application context within the DEAP project

Paper A provides an identification of task and challenge themes in the application Work Packages in the DEAP project—which represent the immediate context and activities within the DEAP project. The occurrence of tasks and challenges in the project is in some ways different from what would be expected in more mature NPD: A wide occurrence of *concept development* is seen, which may be connected to the development of a demonstrator incorporating a novel technology; increased understanding of the performance and behaviour of the technology leads to new concepts and resources limit some development paths—requiring new concepts to fit to new constraints.

Figure 5.1 shows the number of challenge entries—organised by themes identified in paper A—reported in monthly reports mapped to the time-line of the DEAP project. *System development* challenges reoccur frequently in three Work Packages and is the most frequent challenge—representing challenges in developing Technology Prototypes. *Robustness* also represents

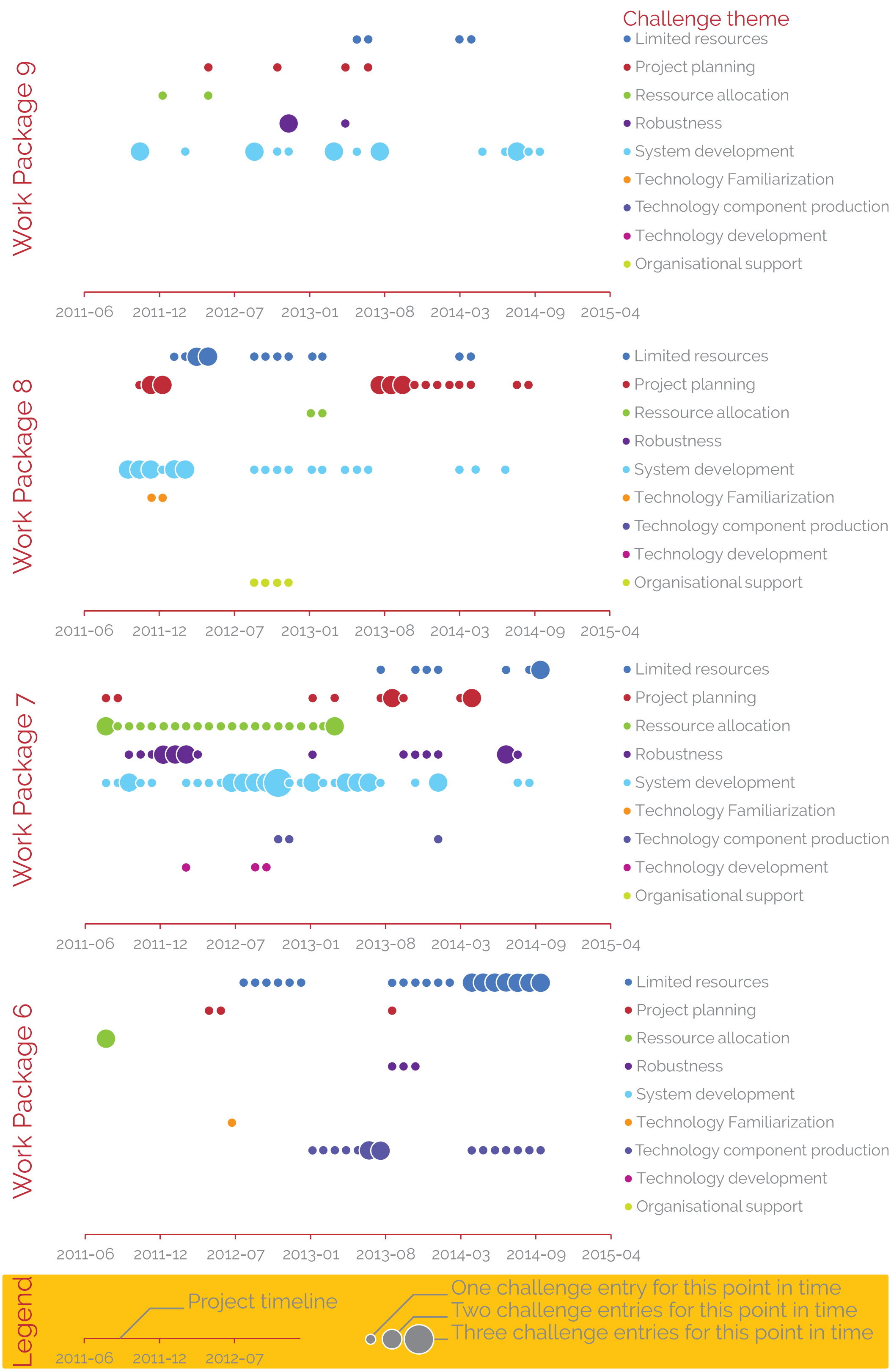


Figure 5.1: A time-line overview of the challenges reported by application Work Packages in monthly reports in the DEAP project (Redrawn from paper A)

a reoccurring challenge in three Work Packages, although its prevalence is substantially higher in Work Package 7 than in the other three Work Packages. *Technology component production* represents a reoccurring challenge in Work Packages 6 and 7—which emphasizes the necessity of having production capabilities in place that can provide reliable production of prototypes for potential customers to support development of products incorporating the novel technology. Organisational and resource challenges occur in all four Work Packages—*Limited resources, Project planning, Resource allocation* and *Organisational support*—but these are less related to technology development than the other challenges.

Paper B defines *Technology Prototypes* as prototypes developed to investigate and demonstrate the performance of a novel technology and identifies the importance of Technology Prototypes as means for investigating uncertainties regarding a novel technology's performance in a potential application. As illustrated in figure 5.2, Technology Prototypes take the output of technology development and integrate this as technology input in a new technology prototype product architecture to investigate the technology's performance in a new application.

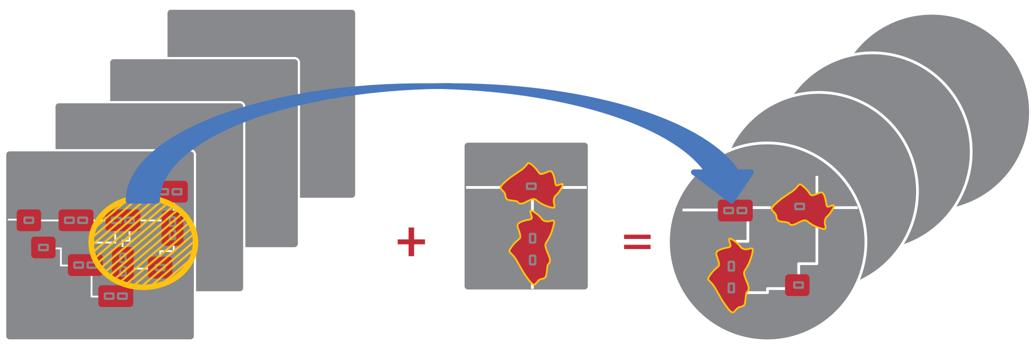


Figure 5.2: The output of the development of Work Package 3, using the Product Technology Architecture, is the tech input into Technology Prototypes (Redrawn from paper B)

Paper B presents arguments for the inapplicability of architecture modelling methods from NPD for technology development—here as a support for Technology Prototypes: the NPD methods are not aimed at overcoming uncertainties present in technology development projects, do not propagate the specific purpose of Technology Prototypes, focus on modularization to optimize product or product program design, and assume knowledge of the product at a greater level than is present in technology development. The purpose, explicitly expressed in the Technology Prototype Product Architecture Tool, is especially important when multiple organisations are involved—to negotiate a common goal for the Technology Prototype. The Technology Prototype Product Architecture Tool is presented and its implementation in the application Work Packages is described in the paper. The results of the implementation indicate that the Technology Prototype Product Architecture Tool provided support to Technology Prototype development.

5.1.3 Challenges met during platform development in the DEAP project

The challenges encountered in the case can be classified into themes. Figure 5.3 shows a word cloud where the font size indicates the relative frequency of words in the challenges section of monthly reports.

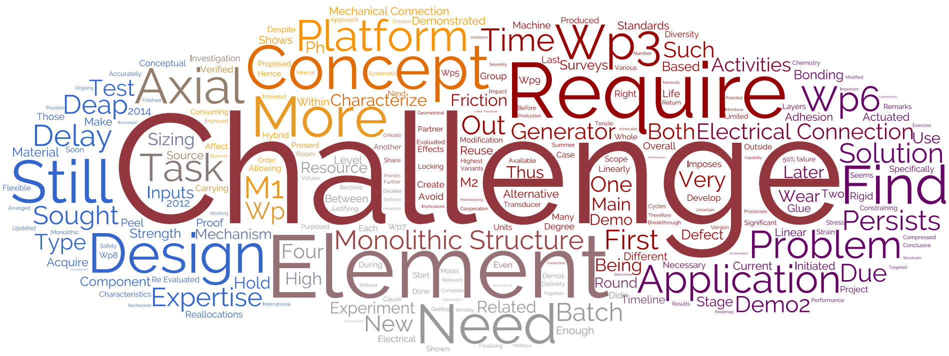


Figure 5.3: A word cloud of the most frequently used words in the challenges section of Work Package 3 monthly reports gives an indication of the breadth of the challenges met in the platform development.

Platform concept development Developing the core of the platform in conceptual form was challenging. This required gaining an overview of the technical solution space, the identified application requirements, and evaluating what should be included and excluded in the platform. Although application requirements had been identified, these were very uncertain as none of the DEAP project applications had experience with DEAP transducers and since no DEAP transducers were in operation in commercial products, no direct analogies could be made.

Developing concepts for the wide span of applications in the DEAP project and other potential applications meant that a large solution space needed to be considered. When concept development was well ahead, the challenge of identifying Product Technology component reuse possibilities that would not introduce detrimental compromises to performance arose. To gain an overview and understanding of the application in the DEAP project, posters based on the PFMP customer view were made to gather information on application requirements and characteristics—shown in figure 5.4. In addition to the analysis of applications within the DEAP project a search for viable applications outside of the DEAP project was performed throughout the project, which was gathered and communicated in reports, overviews, and a classification scheme for potential DEAP transducer applications. This work supplemented the information from applications within the DEAP project and provided a broader decision basis for platform development work.

Identifying and determining the design rationale for Product Technology component alternatives—defining what tasks to use resources on and their goals—was a challenge as there was a need to both identify how the solution space could be classified and what was actually required of the Product Technology components. The Product Technology Architecture—described in section 5.2—with its entity relational modelling between application requirements and Product Technologies provided support in identifying and defining the

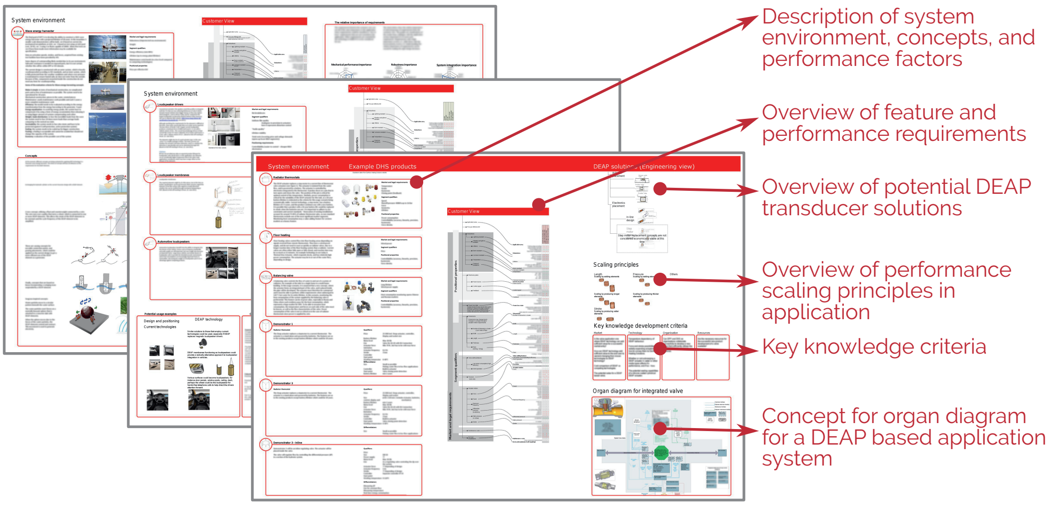


Figure 5.4: Posters were made to collect and provide an overview of DEAP project application characteristics and requirements

design rationale for Product Technologies. Risk management played a role here, as multiple Product Technology component alternatives were defined when reaching the goals of higher performing alternatives was seen as uncertain—multiple alternatives indicated the 'plan B' if the higher performance levels could not be reached within an acceptable time-frame.

Product Technology component development Developing the Product Technology components—the organ alternatives of the Product Technology Architecture model in paper E—proved challenging. The uncertainties of technology development were challenging, as searching for solutions for e.g. mechanical and electrical interfaces were both time consuming and required iterations, testing of hypotheses, simulation models, and extensive testing before reaching satisfactory performance. Despite having access to some of the foremost experts in DEAP technology and taking contact with industrial producers of analogous materials, no existing solutions to these problems could be identified—technological knowledge had to be created along the way. At the core of these challenges was the lack of information available on how to design and dimension these Product Technology components and what phenomena dictated the feasibility of solutions. Experimentation with various solutions, theoretical work on identifying the effects that were at play, and detailed finite element simulations were fundamental in overcoming these challenges.

Furthermore, characterization of both performance and performance goals was challenging in many cases as commonly used parameters fit poorly with the DEAP technology. An example is characterization of monolithic strength, where available standards assume much higher material stiffness than that of the DEAP film. The development of monolithic structures also required additional expert resources, as the competences were outside the initial scope of the Work Package. When they had been identified, key performance factors were added to the Product Technology Architecture model to provide an overview and status for reaching performance goals.

Constructing prototypes for application demonstrators The challenges concerning DEAP transducer design and production for use in application demonstrators in Work

Packages 6–9 related to determining their specifications with application Work Packages—complicated by the technology novelty—their production and reaching the intended performance. The determination of their specifications presented challenges in three ways:

1. Uncertainty of the required performance in a particular configuration in the application, due to lack of experience with the technology in such a configuration

2. As more was understood about the DEAP technology, its value proposition in the application, and technical feasibility within the DEAP project, changes were made to Technology Prototype concepts in some work packages that changed the requirements towards the DEAP transducers.

3. To optimize consumption of the limited resources in the project, partial reuse of transducer design was sought when feasible, which meant that some coordination of prototype specifications was needed across Work Packages. This was challenging to achieve without the compromises becoming too great.

An analysis of the impact of introducing new prototype variants on the resources of Danfoss PolyPower was made, on the basis of prototype and production architecture compliance and an investigation of resource consumption due to changes to performance and features in prototype variants. The results of this analysis—shown in figure 5.5—provided support for deciding which changes to include on the basis of expected value contra impact on resource consumption. A roadmap for development of the Product Technologies and DEAP

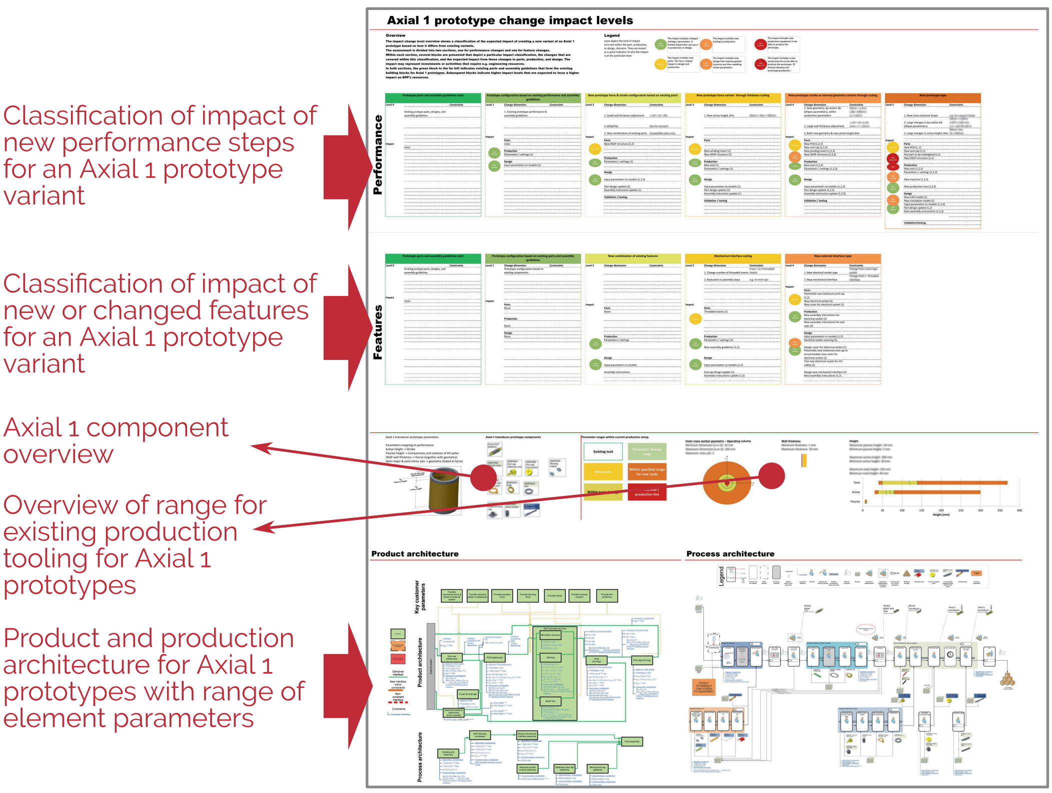


Figure 5.5: An overview of the impact of new feature or performance variants for Axial 1 prototypes was created to support decisions on new variants

transducer prototypes from the Product Technology Architecture was also instrumental in coming to agreement with application Work Packages on what could be delivered for integration in Technology Prototypes.

The challenges concerning production of the transducers lay in production quality—leading to both problems in delivering transducers for testing and in achieving a lifetime that was long enough to finalize application demonstrator tests. Often, these challenges lead to revisiting the Product Technology components—e.g. the electrical interface—as faults were found when testing the transducers in the application Work Packages that necessitated further development of the Product Technology components.

Reaching the intended performance relied on progress in material performance—within Work Package 1—which proved more difficult to achieve than initially estimated. While the initial plans aimed at progressing through three new versions of the material—each providing considerable performance improvements—only the first new version was implemented successfully within the DEAP project. This had detrimental results on the achievable performance in transducers delivered for use in the later Technology Prototypes.

5.1.4 Reflection on results related to RQ1

The technology development context of the project had an effect on both its progress and its goals. The interviews shed light on the context and required output of a technology development project aiming at commercialization. While the number of interviewees does not provide grounds for arguing that the results provide a definitive description of the context of commercialization of a new technology, these results are indicative of the context of both the DEAP project and of technology development on a more general scale.

The core result of the interviews concerns (1) the importance of functioning, robust, prototypes—or products—in an application environment, (2) that demonstrating unique, relevant, properties in an application significantly improves a technology's value in that application, and (3) that developing critical production capabilities is of significant value for proving the ability to produce product on an industrially relevant scale.

Technology Prototypes in the the DEAP project demonstrated a limited subset of the optimal functionality in agreement with the purpose of each Technology Prototype iteration. Tests using Technology Prototypes provided learnings that were valuable to both technology development and evaluation of the use of the technology in each tested application. These experiences corroborate the statements from the interviews regarding value of functioning prototypes even if they do not fully match the application—in functionality, performance or scale. The Technology Prototype Product Architecture Tool provided support within the DEAP project in achieving agreement of the purpose of each Technology Prototype—facilitating a unification of expectations for what results each Technology Prototype would provide.

The application overviews provided an early overview of application requirements and advanced application understanding while defining the initial concepts for the Product Technology Architecture. The Technology Prototypes were also instrumental in acquiring a more in-depth understanding of application requirements. Initial application requirements were somewhat diffuse and imprecise—through Technology Prototype iterations a much greater understanding of application requirements was gained. Concept development tasks in application Work Packages reoccurred in part due to greater understanding of unique properties of the technology in each application—which was emphasized as being important in the interviews. The analysis of external applications through application classifications supplemented the DEAP application information during platform development.

The inapplicability of mature NPD architecture modelling approaches in technology development is argued in paper B on the grounds of the specific circumstances that technology development presents: high technological uncertainty and changing elements of the technology prototype as the technology advances are not adequately accounted for in NPD architecture modelling approaches.

Overcoming the platform development challenges related to scoping was facilitated by the application overviews and the Product Technology Architecture model. Linking application requirements to Product Technologies, design rationale, performance goals, and providing a common overview—as discussed in section 5.2—supported dialogue and structuring of the solution space.

Expert knowledge and extensive development and testing activities were instrumental in overcoming technical challenges—when no existing solutions were to be found. The access to application experts in the application Work Packages can be viewed as an expert resource in this respect when it comes to the work related to applications within the DEAP project.

Seeking reuse across heterogeneous Technology Prototypes illustrates the need to balance resource use by ensuring sufficient commonality, while facilitating the investigation of the technology's unique properties as applicable to each application Work Package. This balancing act is strongly related to the development of the Product Technology Architecture—too specific solutions limit the preparedness of the Product Technology Architecture to fulfil varied application requirements while too generic solutions cannot adequately fulfil the specific application's requirements. Being aware of the impact of new prototype variants and a clear purpose for each Technology Prototype facilitates constructive dialogue of the cost and benefits of commonality and unique design solutions.

Reaching desired performance in DEAP transducer prototypes was hindered both by not achieving the desired material advances and by challenges in reaching desired production quality. Due to the lack of production quality, DEAP transducer prototypes that were not robust enough had to be delivered for integration in Technology Prototypes until production quality issues were overcome. This resulted in robustness challenges in application Technology Prototypes—which caused difficulties and delays in testing Technology Prototypes. These experiences support the statements from the interviews regarding the importance of robust, functioning, prototypes.

The results of implementing the Technology Prototype Product Architecture Tool in the DEAP project indicate that architecture modelling that addresses the particular challenges in technology development can provide valuable support to technology development projects.

In simplified terms, the context and challenges covered indicate the need for a clear vision of the goals of technology development—meeting future application requirements in a unique way—a clear overview of what is needed to get there—expertise, resources, Product Technologies, and production capabilities—and a rigorous development and testing regime to identify and overcome the uncertainties along the way. As many important realisations turn up during technology development and uncertainties are clarified along the way, this is a dynamic and to a high degree unpredictable context—characteristics which must be accounted for in tools meant to support technology development.

5.2 Results related to Research Question 2

The results presented in this section have been published in the following papers:

Paper C	
Title:	*Platform based design of EAP transducers in Danfoss PolyPower A/S*
Authors:	Rahimullah Sarban and Tómas Vignir Guðlaugsson
Conference:	Electroactive Polymer Actuators and Devices (EAPAD) 2013
Research Question:	RQ2.2
Status:	Published
Paper D	
Title:	*Electro-Active Polymer (EAP) high-level product architecture*
Authors:	Tómas Vignir Guðlaugsson, Niels Henrik Mortensen and Rahimullah Sarban
Conference:	Electroactive Polymer Actuators and Devices (EAPAD) 2013
Research Questions:	RQ2, RQ2.2, and RQ2.3
Status:	Published
Paper E	
Title:	*Front-end conceptual platform modelling*
Authors:	Tómas Vignir Guðlaugsson, Poul Martin Ravn, Niels Henrik Mortensen and Rahimullah Sarban
Journal:	Concurrent Engineering: Research and Applications
Research Questions:	RQ2, RQ2.1, RQ2.2, and RQ2.3
Status:	Published

In section 1.3.1, RQ 2 and its supplemental RQs were stated as follows:

Research Question 2 How can a Product Technology Architecture be modelled during technology development as a way to structure the development of a foundation for multiple product platforms?

Supporting Research Question 2.1 What can be constituted as relevant modelling elements to be included in a Product Technology Architecture model during technology development, where the product and production architecture descriptions are not yet complete?

Supporting Research Question 2.2 How can the functional aspects of a product architecture be modelled during technology development in such a way that a Product Technology Architecture's capabilities can be discussed and communicated with stakeholder groups in support of the development of the Product Technology Architecture?

Supporting Research Question 2.3 Through what mechanisms can architecture models support platform development in an early phase of simultaneous product technology and production development?

5.2.1 Product Technology Architecture modelling framework

Paper E describes the theoretical foundation for the Product Technology Architecture and relates the research to literature[1]. The aim of the Product Technology Architecture is to support early phase platform development in which the following is lacking:

1. A clearly defined market or market knowledge
2. Existing products to base a platform on
3. Matured production processes

Paper D presents a vision of the role of the Product Technology Architecture[2] in an early phase of concurrent development. As illustrated in figure 5.6, the Product Technology Architecture is envisioned as a foundation for multiple product platforms—providing a collection of technologies and principles for use in the product platforms—and must, as such, be aimed at fulfilling broad requirements. In this vision, the Product Technology Architecture must still be scoped and delimited to maintain the solution space within the technological expertise of the firm and be used to identify and evaluate when there is a need to expand it.

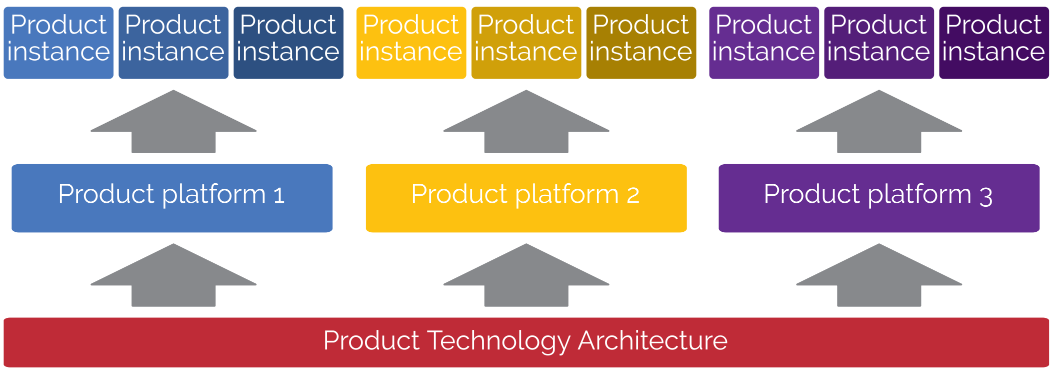


Figure 5.6: The Product Technology Architecture was envisioned as the foundation for multiple product platforms as the DEAP technology development progressed and became commercialized in multiple product families. (redrawn from paper D)

Paper D defines the basis for the Product Technology Architecture modelling framework, which is further covered in paper E. The organ is defined as the central concept in use to indicate technological solutions—with organ alternatives representing alternative Product Technologies providing central functions. Using organs to represent Product Technologies in the architecture provides a definition from an early phase that can evolve and progress in concreteness as the development progresses and the Product Technologies are more completely defined.

The scope of the Product Technology Architecture covers the standardization of principal solutions and technology use within a product portfolio—excluding detailed part design.

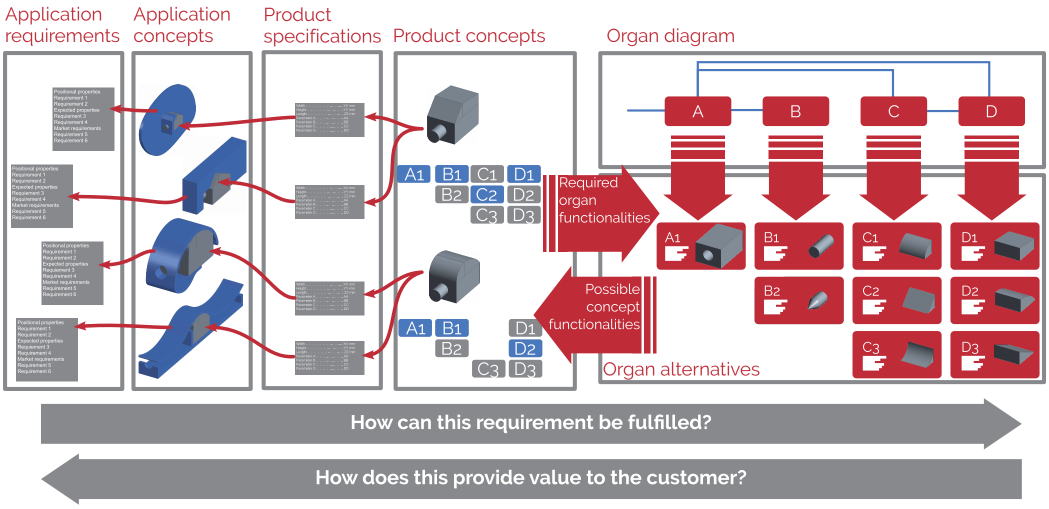


Figure 5.7: A symbolic representation of the modelling elements of the Product Technology Architecture (Redrawn from paper E)

The modelling formalism for the Product Technology Architecture model is illustrated in figure 5.7.

The entity relations between modelling elements aim at providing two directions in which the application requirements and technology components are mapped to each other:

- Each modelling element is directly related to its nearest neighbour and by following the relations from left-to-right, the realization of application requirements can be identified.
- Similarly, in a right-to-left reading order, the value of organs—technology components—can be identified by viewing where the particular organ alternative is perceived to be valuable.

The Product Technology elements in the bottom right of figure 5.7 are in this way directly related to transducer concepts and application requirements while being decoupled from individual applications.

5.2.2 Case implementation results

Paper C presents the preliminary platform description—based on the PFMP—for a DEAP technology based product family, including

- application requirements
- classification of applications and performance requirement ranges

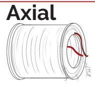
[1]In the appended papers, the name of the support being developed varied. In this thesis the term Product Technology Architecture modelling framework is used as consistently as possible to reflect the view of the author at the end of the research project.

[2]referred to as the product concept platform and Pre-PFMP in the paper

- the preliminary identified functional principles required to enable construction of DEAP transducers from the platform
- partial overview of preliminary part variants required within the platform

The DEAP transducer type concepts that would be made possible by the developed functional principles and their intended performance features are modelled in paper C—an overview of their comparative performance on key performance parameters can be seen in table 5.1.

Table 5.1: The range of performance identified necessitated a broad range of DEAP transducer types to be conceptualized (Reproduced in part from paper C)

	Potential application	Loading possibilities	Typical force range	Typical stroke range	Typical freq. range	Cycle range	Overall serial resistance
Axial 1 	Linear positioner	Compressive and tensile	Medium	Medium	Medium	Mega	$< 5\Omega$
	Vibration generator			Low	high	Giga	
Axial 2 	Surface pressure gen.	Tensile	Medium	N/A	Low	Mega	$< 100\Omega$
	Linear positioner		Medium	Medium	Medium		$< 5\Omega$
	Linear sensor		N/A	High	Low		$< 100\Omega$
Linear 	Linear Positioner	Tensile	High	High	Low	Mega	$< 5\Omega$
	Energy Harvesting				Low		

The identified application requirement classifications are mapped to DEAP transducer concepts. Figure 5.8 shows a sketch of a transducer concept primarily aimed at generator applications.

Paper C presents Danfoss PolyPower's perspective on the preliminary results of the development at the time of writing, along with the rationale behind choosing a platform based development approach.

The results presented in paper C represent the preliminary progress of the platform development. Classifying identified application requirements forms the basis for identifying what

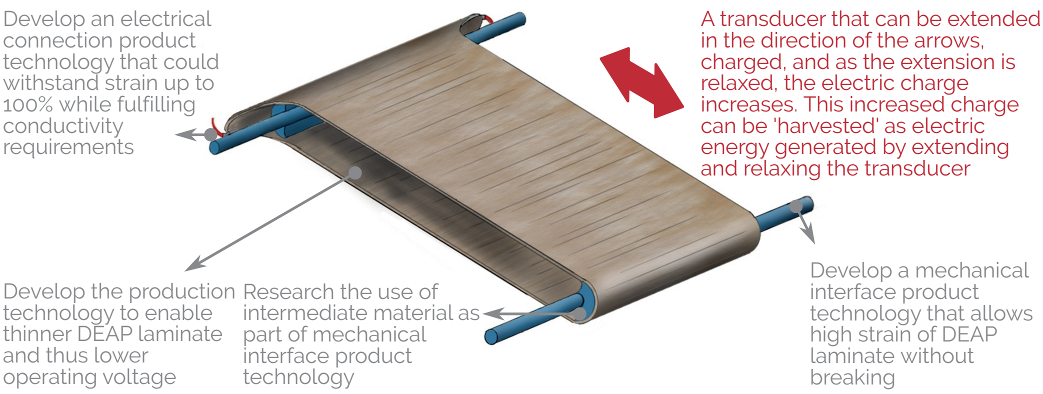


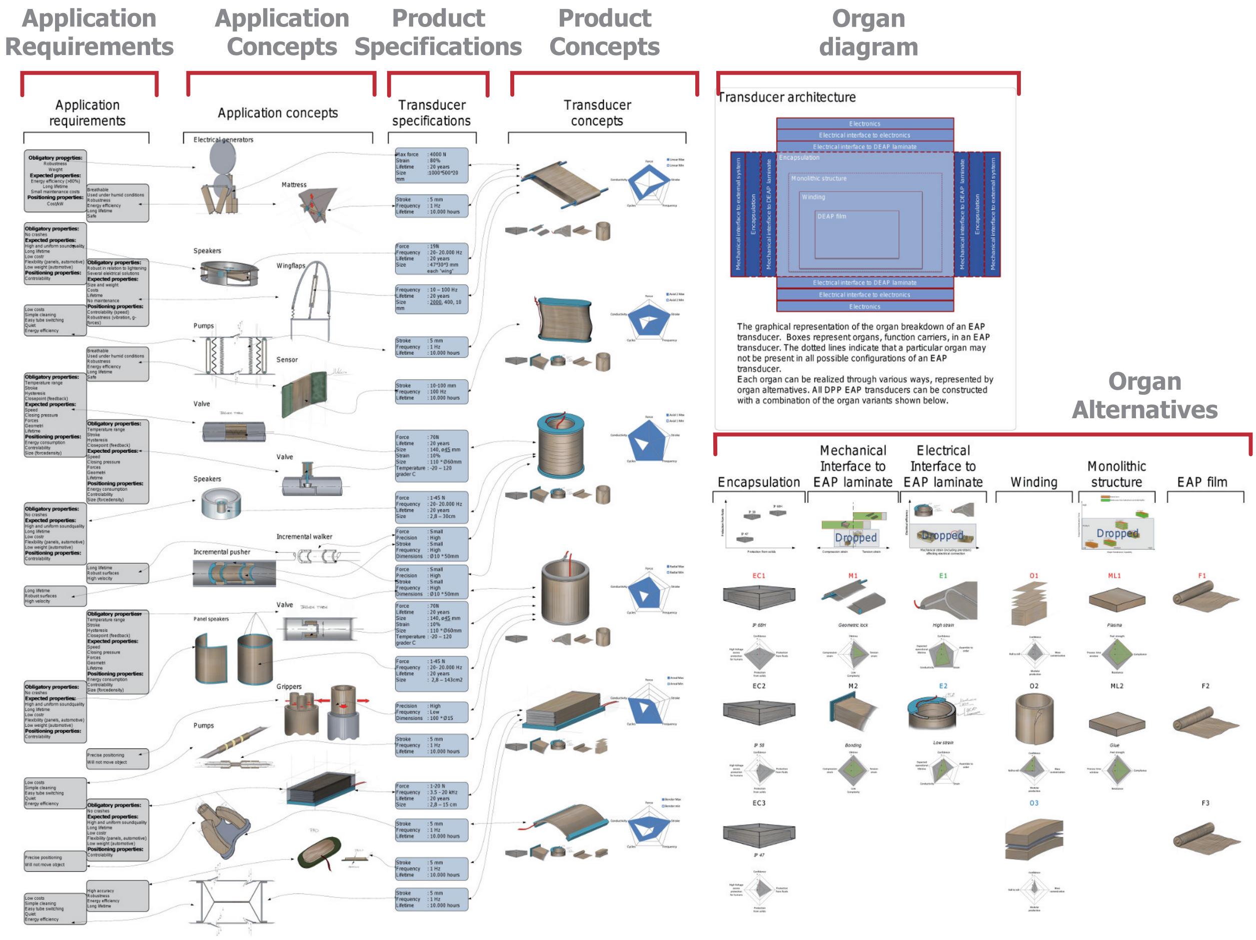
Figure 5.8: A sketch of a 'linear' type transducer—with developed product technologies marked and described (adapted from paper D)

technical performance is required from platform components. By identifying functional principles and on that basis, DEAP transducer types that could fulfil application requirements, a platform could be defined and the activities required to develop it could be defined and initiated.

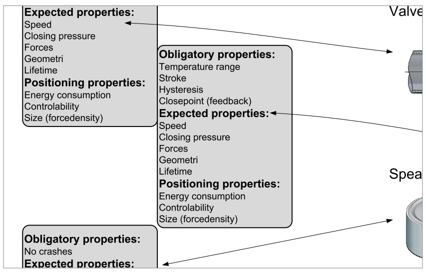
The results of application classification and subsequent mapping to components highlight the breadth aimed at by the platform development and the necessity—for Danfoss PolyPower—of being able to construct a wide range of DEAP transducer types. As the market was uncertain, the precise requirements of future customers had not been identified but the application to component mapping provided evidence that a wide range of potential application requirements could be fulfilled. The limitation of performance represented by the performance ranges aimed at—though wide—provided scoping for the development project.

The Product Technology Architecture model in the DEAP project—presented in paper E—contained:

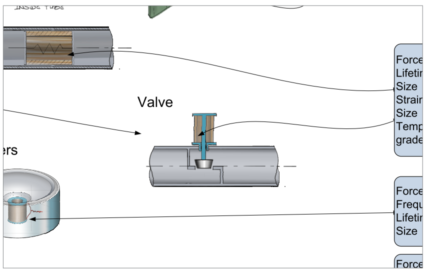
- Application requirements (figure 5.9a)
  - describing a prioritized list of central application requirements identified for a variety of potential applications
- Application concepts (figure 5.9b)
  - Sketches of identified application concepts, in which the use of DEAP transducers in illustrated for inspiration and clarification
- Product specifications (figure 5.9c)
  - A list of critical identified product specifications for DEAP transducer type fitting to each application concept
- Product concepts (figure 5.9d)
  - An illustration of a DEAP transducer concept, the organ alternatives it comprises, an a radar-chart indicating the intended performance range on critical performance parameters
- Organ diagram (figure 5.9e)
  - A graphical representation of the generic organ composition of DEAP transducers, where some organs are *optional*—may not be included in all DEAP transducer types.
- Organ alternatives (figure 5.9f)
  - A categorized list of organ alternatives for each of the organs in the organ diagram (the DEAP transducer architecture). The performance mapping of the organ alternatives is shown on a graph for each group of organ alternatives and each organ alternative has two performance ratings on critical parameters: *Intended* and *achieved*. *Intended* performance indicated the goals of the development task and *achieved* performance indicated what had been achieved when the model instance was created.



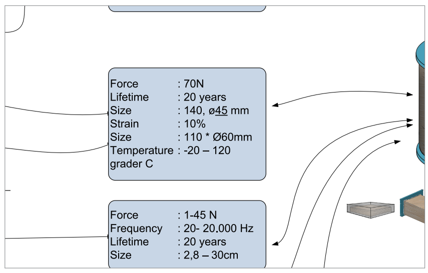
The Product Technology Architecture model



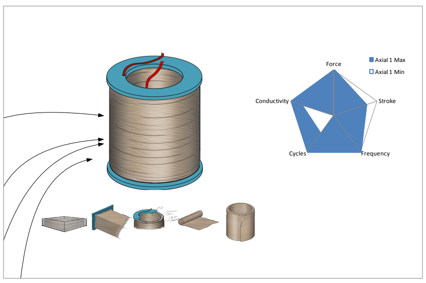
(a) Application requirements



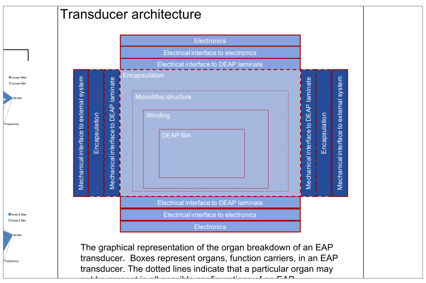
(b) Application concepts



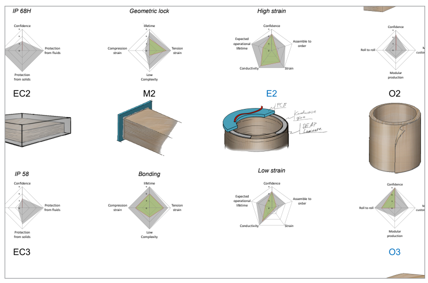
(c) Product specifications



(d) Product concepts



(e) Organ diagram



(f) Organ alternatives

Figure 5.9: The Product Technology Architecture modelling framework and its modelling elements (reproduced from paper E)

Paper D describes the contents of the DEAP Product Technology Architecture[3] model in each modelling element, the detail level in the DEAP Product Technology Architecture model, and the use of supplementary documents to cover details not included directly in the Product Technology Architecture model.

The DEAP Product Technology Architecture was used to support concept evaluation and elimination based on ability to fulfil multiple application requirements and organ alternative sharing. Two mechanisms provided by the Product Technology Architecture were central to these tasks:

- reducing the technical solution space with limited compromises in the ability to fulfil application requirements
- decoupling technical solution development from individual applications as DEAP applications were considered uncertain

The use of a physical, large-format poster, version of the Product Technology Architecture as a dialogue tool with stakeholders inside and outside the Work Package team—which is elaborated in table 5.2—was considered valuable and a facilitating factor in meetings. The

Table 5.2: An overview of the various uses of the DEAP Product Technology Architecture model in the DEAP case (Reproduced from Paper E)

	Communication form	**Utilization dimension**
Participants from platform development work package	A poster showing the Product Technology Architecture model has been hung on the wall during meetings with other work packages	Track performance goals for organ alternatives Link development tasks within the platform to application context and to other work packages Provide a platform perspective during discussions on tasks within platform development Decide focus of organ alternative development tasks based on design rationale Evaluate the contribution of organ alternatives to the platform to make decisions on which development tasks to continue and discontinue
Participants from other work packages	A poster showing the Product Technology Architecture model has been presented during meetings with other work packages and hung on the wall during meetings with other work packages	Present platform contents and capabilities Link development work in the other work packages to the platform development to identify performance factors for platform Communicate platform capabilities during concept development for key applications
Steering committee	Parts of the Product Technology Architecture model have been presented in presentations at steering committee meetings to provide an update of the progress in the development of the project	Prioritize focus areas and resources within the DNATF DEAP project Evaluate platform potential and platform development work with focus on platform capabilities and feasibility of development work
Customers visiting Danfoss PolyPower offices	The Product Technology Architecture model has been presented to visitors to Danfoss PolyPower offices, both customers and potential customers	Present platform contents and capabilities Discuss potential platform solutions for customer's application

[3] denoted Conceptual Product Platform in paper E and product concept platform and the model as Pre-PFMP in paper D

hand-sketched illustrations were considered to communicate ideas well without indicating that the ideas were fully developed.

5.2.3 Reflection on contribution

Paper C presents the preliminary foundation for the subsequent work in the research. Classifying identified application requirements and subsequently mapping them to technology components provided a basis for further evolving both the platform being developed and the Product Technology Architecture model.

Paper C answers RQ2.2 by providing an overview of identified application requirements in a format that was used to identify likely required performance ranges. By then characterising the feasible performance ranges of DEAP transducer type concepts, the DEAP concepts could be mapped to identified application requirement classifications. This constitutes a relational link between potential applications and the functional aspects of the Product Technology Architecture.

A quantified PFMP for a DEAP transducer product family was furthermore presented in paper C. The direct quantification at this level of detail was abandoned in the Product Technology Architecture model—in favour of using detailed reports for such quantifications—as the dynamic environment of the development project meant that as soon as the contents had been quantified, they had become obsolete. This presented hurdles when discussing development tasks as the discussions began to focus on technical details of obsolete models instead of the activities ahead and their tasks and challenges.

Paper D served to communicate architecture based development to the DEAP research community—providing opportunity for feedback on challenges and role of architecture based development for DEAP based technology.

By discussing the role of the Product Technology Architecture as a feeding platform for subsequent product platforms as the technology becomes more mature helped in framing the scope of the Product Technology Architecture model in the further research. While the interplay of the Product Technology Architecture and subsequent platform development in more mature NPD has not been investigated in the research this framing was valuable in the development of the Product Technology Architecture.

The subtasks of the development project focused on developing the organ alternatives—each with their own design rationale in DEAP transducer type concepts. The breakdown of DEAP transducer into organs and their use to represent development tasks, is a partial answer to RQ2.3, as identification and breakdown of development tasks is an important step in any development project.

Paper D presents a partial answer to RQ2 through the preliminary Product Technology Architecture model. RQ2.2 is also answered in part in the paper through the inclusion of applications and application requirements coupled with the mapping between applications through DEAP transducer concept types to the organs on the right in the preliminary Product Technology Architecture.

The main contribution of paper D is the definition of the Product Technology Architecture model, its elements, and their interrelations. The preliminary Product Technology Architecture model is presented as the *Pre-PFMP* in the paper. This terminology stems from the view at that time in the project that the model would in time morph into a PFMP. Later in the research, this view changed as the use and value of the Product Technology Architecture model in the project as an overview at a Product Technology level coupled with details in supplementary documents, was observed. In this thesis, the terms used in the papers have been replaced by the term Product Technology Architecture as it better reflects the perspective of the researcher at the final stage of the research project. This definition provides a framework for other researchers and practitioners to apply the Product Technology Architecture model in their own work.

The case description supports the usefulness of the Product Technology Architecture model by documenting its implementation in its intended setting in industry. Its use for both planning, evaluation, and brainstorming in the DEAP project showed some of the various means in which the Product Technology Architecture could support platform development at a technology development stage.

Paper E addresses RQ2 and RQ2.3—in the Product Technology Architecture's implementation in the DEAP project, the Product Technology Architecture was used to structure the foundation of the platform development project. The description of the technical solution space being considered as technical solutions, each with a particular set of performance ranges, and linking these with DEAP transducer and application concepts was used as a basis for comparative concept evaluation and elimination to limit resource demand while maintaining the potential to fulfil broad application requirements. The organ alternatives represented subtasks, where the development goals were to reach the intended performance levels indicated in the graphs—which defined the design rationale behind their inclusion in the platform. In this way, the Product Technology Architecture supported the structuring of the development of a foundation for a product platform.

RQ2.2 is addressed by the left-to-right and right-to-left reading orders providing a path between identified application requirements and organ alternatives—the technology components. These reading orders provide, respectively, a mapping of how a requirement can be realized in the platform and how a technical component provides value by its inclusion in the platform.

The paper describes some of the ways in which the Product Technology Architecture modelling framework supported platform development in an early phase—which addresses RQ 2.3. The use of a poster containing the Product Technology Architecture during meetings as a dialogue tool when planning and reviewing development work in the Work Package, both with stakeholders inside and outside the platform Work Package, supported the platform development by providing a structured approach to the development tasks from an early phase (an overview of various uses of the Product Technology Architecture model is presented in table 5.2).

While the use of the Product Technology Architecture model to communicate the platform's potential capabilities and vision—portrayed through the concepts and intended performance goals—has not been covered in detail, the value of having a communication artefact for this use should not be underestimated. Potential customers need to be able see the potential of the platform to invest resources in investigating the feasibility of integrating DEAP technology into their products. The Product Technology Architecture model provides a tool for this purpose. Part of the value lay in presenting the broad potential capabilities—the predispositions of Danfoss PolyPower's engineers on what provides value for the potential customer can be supplemented by the broader capabilities presented by the Product Technology Architecture model.

Papers D and E support findings from other researchers on the usefulness of boundary objects in the form of physical artefacts that can be manipulated by the stakeholders involved and support unifying perspectives across stakeholder groups.

5.3 Results related to Research Question 3

The results presented in this section have been described in the following papers that have either been published or submitted during the research project:

Paper F

Title:	*Visual modelling of pilot production to support decision making in production development*
Authors:	Poul Martin Ravn, Tómas Vignir Guðlaugsson and Niels Henrik Mortensen.
Conference:	International Design Conference—DESIGN 2014
Research Question:	RQ3, RQ3.2, and RQ3.3.
Status:	Published

Paper G

Title:	*Modelling production architectures in the early phases of product development*
Authors:	Tómas Vignir Guðlaugsson, Poul Martin Ravn, Niels Henrik Mortensen and Lars Hvam.
Journal:	Submitted to a peer reviewed journal
Research Question:	RQ3, RQ3.1, RQ3.2, and RQ3.3.
Status:	Submitted to a peer reviewed journal

In section 1.3.1, RQ 3 and its supplemental RQs were stated as follows:

Research Question 3 How can a Production Architecture be modelled in simultaneous Product Technology and production development to support development decisions regarding the production system architecture?

Supporting Research Question 3.1 What can be constituted as relevant modelling elements to be included in a Production Architecture model in a technology development context, where the product and production architecture descriptions are not yet complete?

Supporting Research Question 3.2 How can the capabilities of a Production Architecture be modelled during technology development in such a way that they can be communicated and discussed with stakeholder groups in support of the development of the production architecture?

Supporting Research Question 3.3 How can planned changes to the Production Architecture that are part of the planned development progress be taken into account in a model of the Production Architecture?

5.3.1 The Production Architecture modelling framework

Paper G presents a definition of a Production Architecture as "the capabilities of the production system and the deliberate organisation of the functions required onto the physical elements of the production system, and the relations between elements." The production task defines what the production system must be particularly good at and frames the development of the Production Architecture. The development of a Production Architecture within a technology development environment is performed within a constantly changing production task—which is affected by the required function of the Production Architecture, the transformation required, and the external environment as shown in figure 5.10.

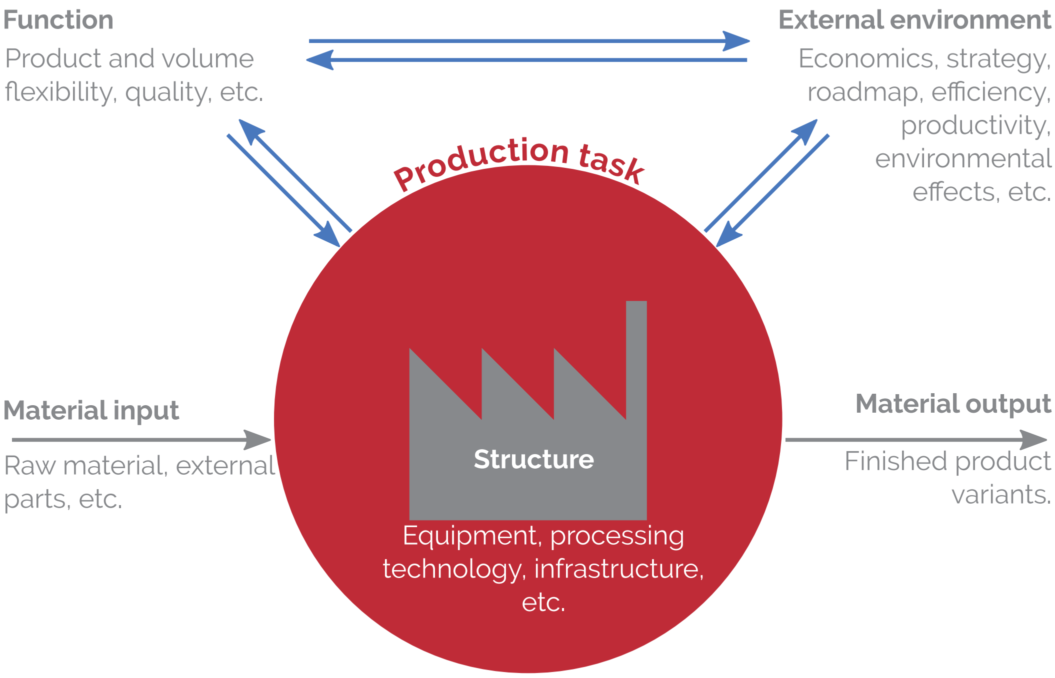


Figure 5.10: A systems view of the Production Architecture showing how the structure of the Production Architecture are dependent on the production task which in turn is determined by the transformation need, the functional requirements, and the external environment. (Redrawn from paper G)

The concurrent development of the Production Architecture and product architecture is an environment where the definitions of both architectures start out incomplete and are gradually made more complete as development progresses. Despite the incompleteness of the architecture definitions, decisions have to be made at an early phase of development on the implementation of production capabilities to enable e.g. process development, investigation of obtainable product quality, and production of prototypes of the necessary quality to investigate applications for the technology. The Production Architecture framework is aimed at supporting these decisions by modelling the Production Architecture.

The following factors regarding the production development task in the DEAP project was contrasted to established production technologies by project participants. When dealing with established production technologies, up to a hundred years of literature on the production technology may be available—in such cases one chooses a suitable production process based on capacity, quality, or similar parameters, and perhaps one optimizes the process further. But in the DEAP project, there is little or no existing knowledge of the production technologies for DEAP technology. What it needs to be capable of now can be specified, but the material and products are still being developed so it is uncertain whether the specifications will hold true in the near future. Therefore, it is necessary to communicate and discuss the production system development and implementation plans with the relevant stakeholders to ensure that implemented capabilities are suitable and timely.

Requirements for what a model of a Production Architecture at an early phase of development should comprise are listed in paper G based on a literature on production systems and their design. They are grouped into three perspectives on the Production Architecture:

- The structure of the Production Architecture
  - the constituent elements and their relations
  - the dispositional links to the product architecture
  - indication of chosen production technology
- The capabilities of the Production Architecture
  - production flexibility
  - volume flexibility
  - indication of relevant processing and setup times, batch sizes and partially produced goods to a fitting detail level
  - product differentiation points
  - indication of obtainable quality
- The expansions to the Production Architecture
  - production volume scaling
  - stepwise capability increases

The literature review in paper G presents the foundation for the contents of the modelling framework, as well as the gap being filled by it: a modelling framework describing the structure, capabilities, and expansions of a Production Architecture fit for use within the dynamic, uncertain, environment in the early phases of concurrent production and product architecture development—an environment lacking both the historical production and product data for approaches founded on utilizing datasets for optimized production system design and incompatible to the completeness in the definition of production and product architectures that other identified approaches aim for.

The modelling elements of the Production Architecture framework are presented in figure 5.11. The three perspectives—structure, capability & expansion—are represented. *Structural* elements describe the physical and process structure of the Production Architecture and provide a link between the constituent elements of the Production Architecture and the product characteristics of the product architecture. *Capability* elements describe the capabilities in terms of product and volume flexibility. In addition to this, process and routing flexibilities can be identified in the structural elements in the Production Architecture. *Expansion* elements describe—through multiple views, layers, or model instances—the planned and potential expansions to the Production Architecture.

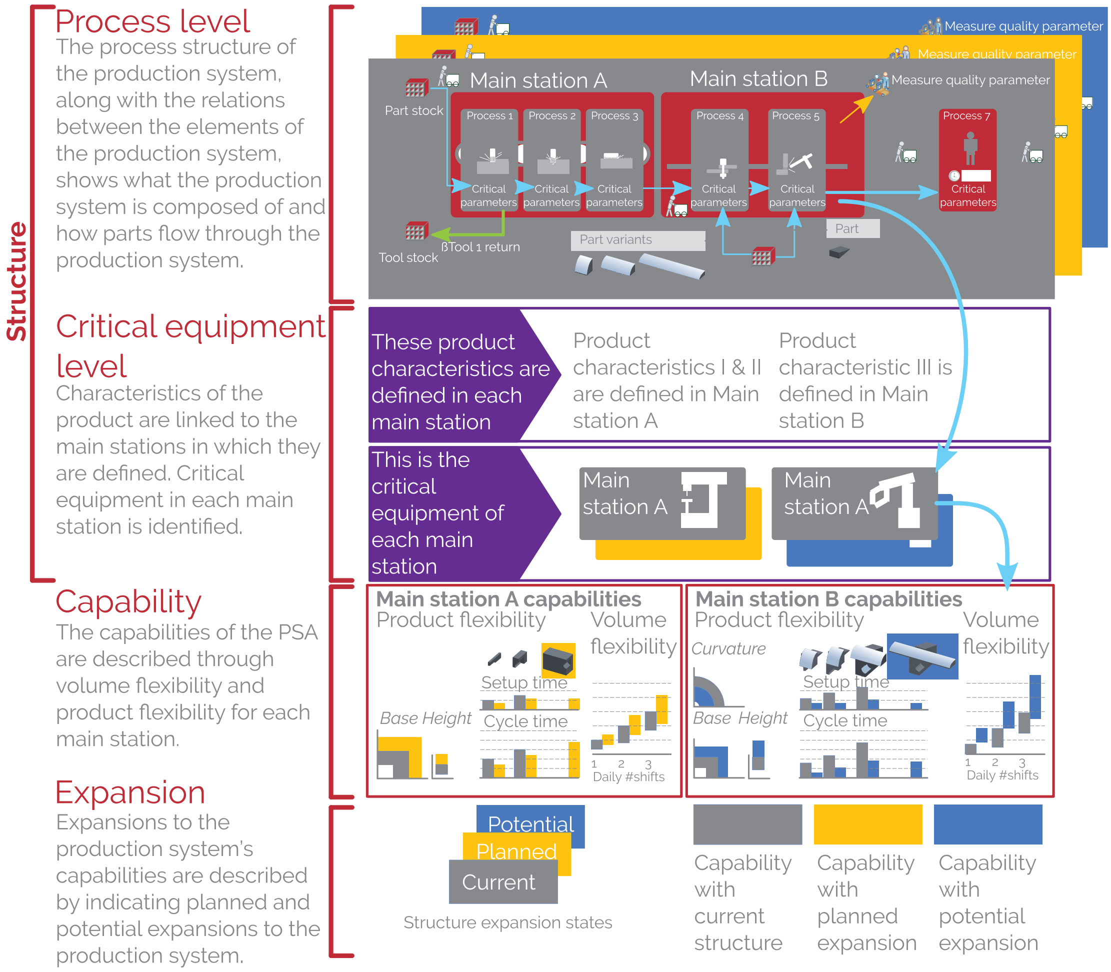


Figure 5.11: The Production Architecture framework modelling formalism overview (Redrawn from paper G)

5.3.2 Results from the case implementation

Paper F describes modelling process for the DEAP Production Architecture models, which is shown in figure 5.12 and contained:

- Investigation of existing—but outdated—documentation of the production process and telephone conference with production manager to clarify production process and requirements
- A workshop with the production manager comprising a presentation of the production process and requirements for model; a walk-through of the production process with the supply chain director; and the collection and presentation of findings by the researchers to verify findings.
- Concurrent draft iteration and modelling formalism refinement
- Workshop with production Work Package team to refine and verify a draft model—and discuss details on the production process and task-benefit matrix
- Model update to reflect results from workshop

- Observing the use of the model with various stakeholder groups at a project symposium and obtaining feedback on the model and it's use through interviews

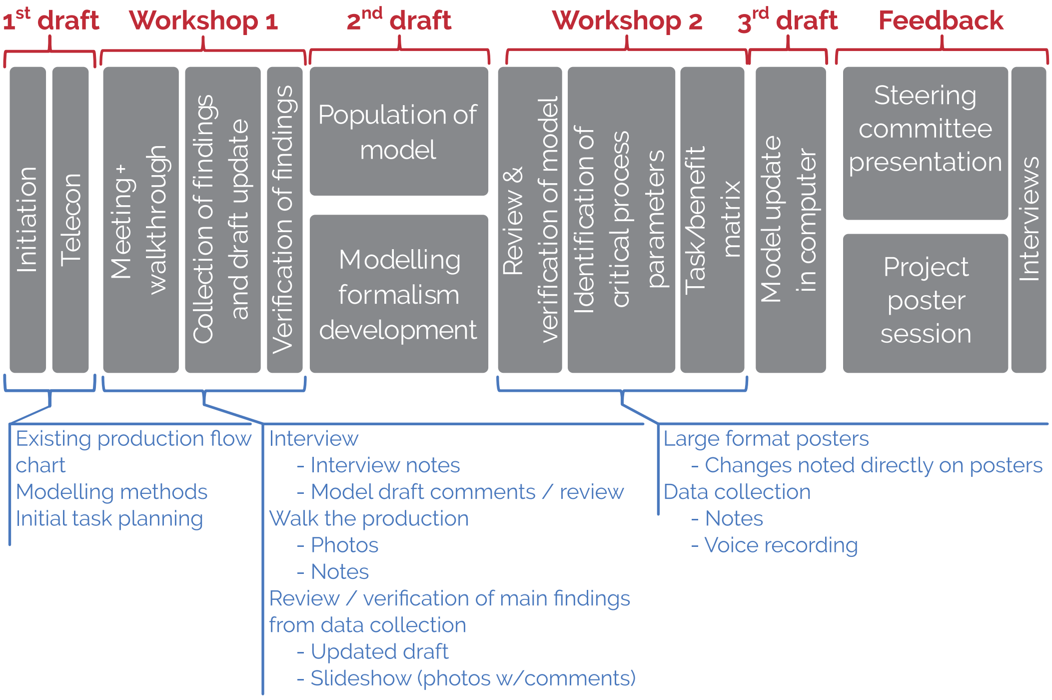


Figure 5.12: The process followed while constructing the Production Architecture models in the DEAP project (Redrawn from paper F)

The use of the Production Architecture framework in the DEAP project surrounding its first implementations are described in paper F and how three perspectives on the Production Architecture were captured and communicated in the DEAP project: its *structure*, its *capabilities*, and its *expansions*.

The Production Architecture models were used as a combined model with supplementary information on project tasks and links between tasks and the capabilities of the DEAP Production Architecture as seen in figure 5.13.

Paper F presents the initial instances of the DEAP Production Architecture models and the preliminary results of the implementation as a tentative answer to RQ3. The proposed approach presents the capabilities of the Production Architecture in terms of the creation of product variants, expected production capacity increases, increased capabilities in the range of product characteristics achievable, and quality related capabilities. These elements provide a tentative answer to RQ3.2. Figure 5.13 shows how multiple instances of DEAP Production Architecture models were used to model planned expansions to the Production Architecture, providing a preliminary answer to RQ3.3.

The results of the implementation of the Production Architecture framework in the DEAP project are further described in paper G. Details of the DEAP Production Architecture models are described and illustrated—see figure 5.14—and the models' use in the project is reported. The case description includes iterations that were done to reflect changes in original plans due to decisions made on which capabilities to implement and due to tasks that proved unsuccessful. The main changes between two major instances of the DEAP Production Architecture model are shown in figure 5.15.

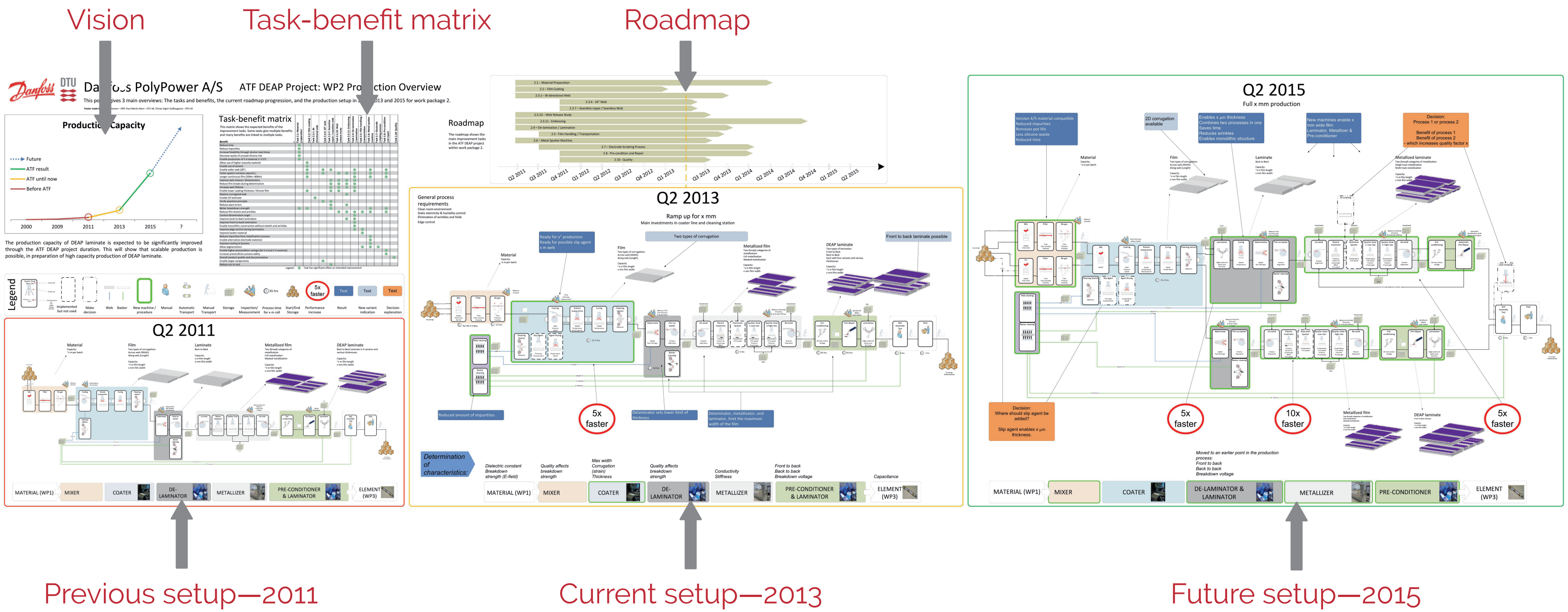


Figure 5.13: Overview of the Production Architecture models in the DEAP project including supplementary information linking the models to development activities (Redrawn from paper F)

Structure

Process level

The de-lamination machine was to be updated for 2015 as a combined de-lamination & lamination main station comprising 5 processes. The flow is indicated with black lines, stock with icons, and tool return paths are indicated with blue and green lines. The main quality control parameters are listed along a QC icon. The critical performance criteria are listed for each process in the main station.

Critical equipment level

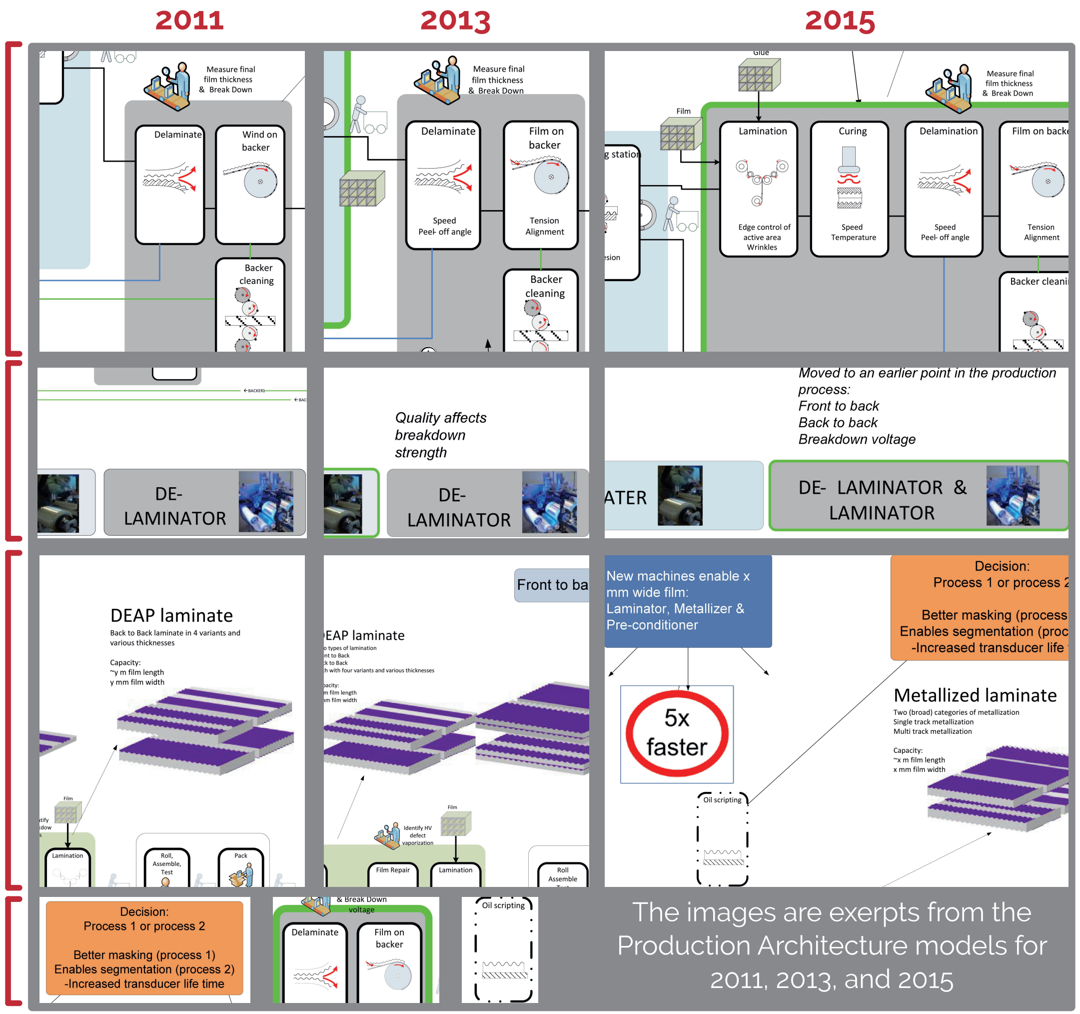
The new piece of equipment—a combined de-laminator & laminator—is indicated at the bottom of the model. Changes from the current state Production Architecture model to where product characteristics are determined are listed directly above the equipment where the product characteristics are determined in the 2014 & 2015 Production Architecture models.

Capability

The capabilities of the new equipment was indicated in three ways. The product differentiation points for basic film configurations was illustrated with graphics along with the maximum or minimum achievable dimensional ranges for product variants. The critical benefits provided by new equipment were noted specifically in blue boxes. The relative throughput increase was indicated inside a red oval in relation to the Production Architecture at the start of the project. In the 2013 version, lamination of films was to be done after metal-deposition, while lamination preceded metal deposition in 2011 and the plans for 2015.

Expansion

Planned expansions are indicated through green borders on main stations and equipment. Potential expansions are indicated as decisions in orange boxes and by using patterned borders—here on a process alternative.



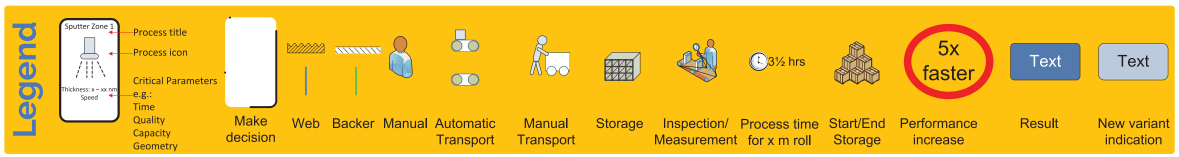


Figure 5.14: Excerpts from the DEAP Production Architecture models (Reproduced from paper G)

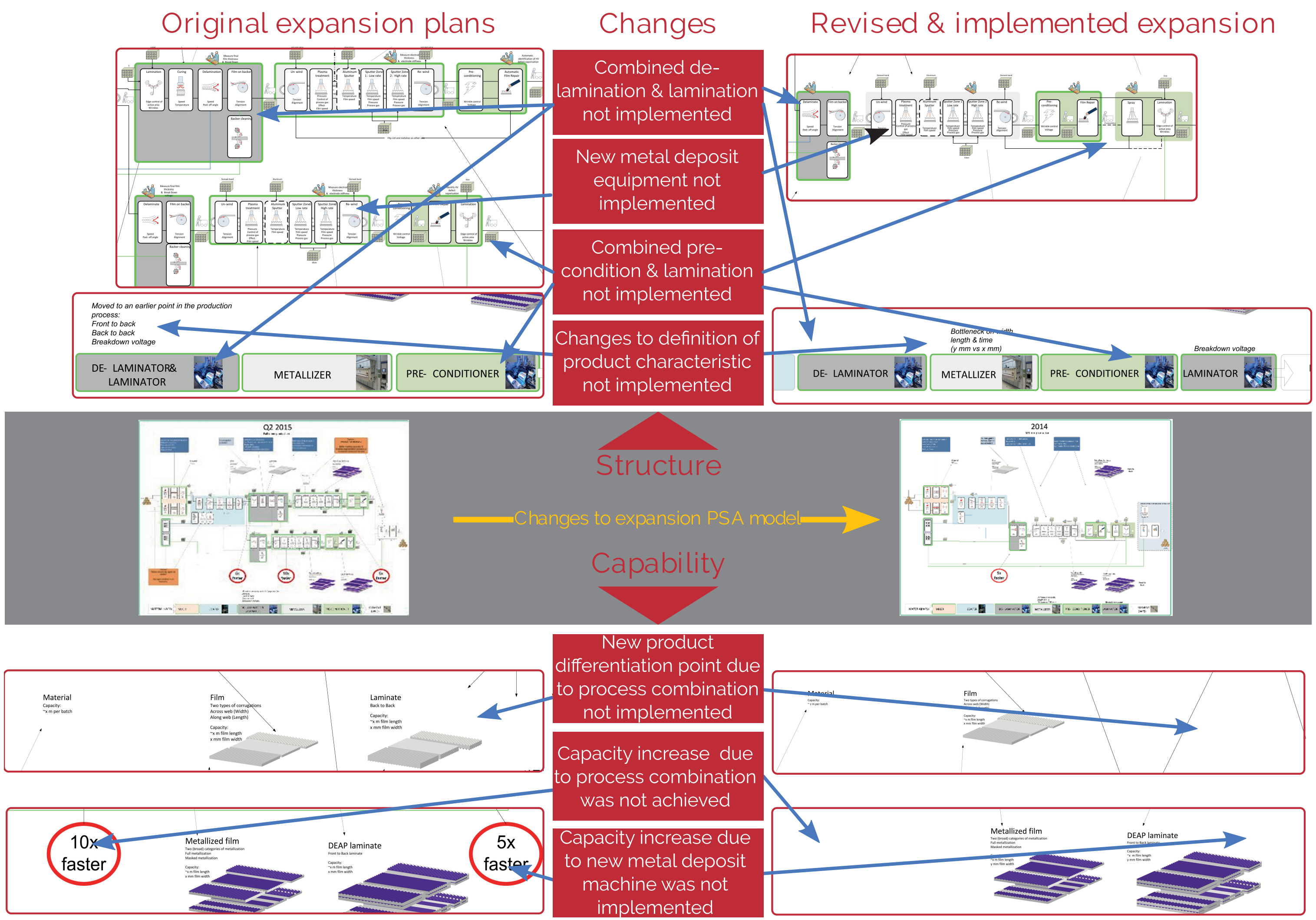


Figure 5.15: Changes to the *future state* DEAP Production Architecture models due to development decisions (Redrawn from paper G)

The DEAP Production Architecture implementation supported capturing and identifying the structure of the DEAP Production Architecture, including e.g. critical process parameters, production technologies, quality control points, equipment, and dispositional links to the product architecture. The capabilities of the DEAP Production Architecture in product flexibility, volume flexibility, and parameters related to obtainable product quality. These were all captured for three instances of the DEAP Production Architecture: start of project, mid-point of project (planned expansions), and end of project (*future state*).

Decisions were modelled in two ways; explicit and implicit. The explicit decisions were highlighted in the models as decisions to be made, but other decisions by the Work Package team were also captured implicitly through the model contents of the future state DEAP Production Architecture model. While concretely modelled, these plans were still up for discussion and some changes were made to those plans following discussions on prioritization of resources.

The preliminary evaluation in paper F of the Production Architecture framework's usability in industry within a technology development context indicated a that the implementation was valuable and that the modelling formalism combined a holistic overview of the DEAP Production Architecture with a detail level that also benefited more in-depth discussions. Paper G further discusses how the application of the Production Architecture framework in the DEAP project indicated that the modelling process facilitated dialogue and contemplation of the production processes in plenum—at a more holistic level and yet also with a greater level of detail than prior to the Production Architecture implementation.

Some of the statements given on the value of the modelling framework include:

> “
> - Hearing how the production team was able to use the models for communication—internally and externally—showed me that it was a good solution. The production team could use it and explain it and use it to explain to others what the production was all about.
> - The information on the production system that was hidden inside our minds has been visualised in the models
> - It's good to use with people that do not have the in-depth understanding of what our production system is about
> - The models give us an overview of the solutions and where potential changes may affect the following processes—do they have a detrimental effect on the other processes?
> - We needed to communicate what is the activity, what is the process, and what is critical—this is captured in the Production Architecture models
>
> ”
>
> *Statements by project participants*

5.3.3 Reflection on contribution

The process followed during the initial modelling initiative—in which preliminary Production Architecture modelling formalism and model instances were created—proved practical. A model was constructed within what was considered a reasonable amount of time that captured and communicated the Production Architecture's structure, capabilities, and expansions to a heterogeneous group of stakeholders.

Using a slide-show combining the researchers' notes on the production process with photos taken during the walk-through—in direct succession to the walk-through—to verify the researchers' understanding of the production process and correct misunderstandings and lacking details provided a good foundation for the DEAP Production Architecture modelling task.

Paper F was a preliminary description of the Production Architecture framework, its development, and its implementation in the DEAP project. Implementing the Production Architecture framework in industry provided a proving ground for the framework and feedback on its applicability, usability and usefulness. In paper F , the preliminary results of the evaluations were presented. Later, more iterations were made in the DEAP project and further evaluations performed.

The results presented in paper F were further refined and described in paper G where the background for e.g. expansion modelling and the modelling formalism and the evaluation of the Production Architecture are addressed further.

Paper G presents a refined description of the Production Architecture modelling framework and its implementation. The main contribution is within architecture modelling—focused on modelling Production Architecture in an early phase of concurrent production and product development.

The paper contributed with an answer to RQ3.2 through the capability modelling in the Production Architecture framework. The implementation provides evidence that it provides a means for communicating to and discussing the capabilities with diverse stakeholder groups to support development.

RQ3.1 is addressed by presenting a literature based list of elements to include in a Production Architecture model at an early phase of development.

The inclusion of expansion modelling elements in the Production Architecture framework, based on similar modelling elements in existing literature, addresses RQ3.3.

The combination of addressing the supporting RQs RQ3.1–3.3 and the description of the modelling elements of the Production Architecture framework addresses RQ3.

The underlying assumption behind implementing Production Architecture modelling as a support for development decisions during concurrent development is that by explicitly capturing and communicating—discussing—central information on the Production Architecture being being developed, leads to better decisions on the development tasks.

Modelling Production Architecture capabilities can facilitate discussions on what capabilities are needed and what is obtained by implementing new equipment in the Production Architecture. Plenum discussions can bring out differences in perspectives on the production capabilities, equipment, and critical parameters, that were otherwise not known.

Production Architecture development at an early phase of development has a different focus than in relation to more mature NPD. The focus is on becoming able to produce the product at all—developing the capabilities to produce the product—while more mature development is focused on optimizing how it is produced and increasing the production performance. Some equipment is critical for determining whether the product can be produced and in what quality and must therefore be developed and implemented. Other equipment of a more generic nature that primarily increases production capacity may not need implementation at an early phase. In the DEAP project, the equipment was not the limiting factor for production volume, but the personnel resources on the production floor. However, the task was to develop the ability to produce the product and prove the feasibility of doing so at an industrial scale—the production volume capacity was not a limiting factor in successfully completing this task.

CHAPTER 6 Conclusion

Antoine Magnan, a French zoologist, in 1934 made some very careful studies of bumblebee flight and came to the conclusion that bumblebees cannot fly at all! Fortunately, the bumblebees never heard this bit of news and so went on flying as usual.

—Ross E. Hutchins, *Insects,* p. 68 (1968)

This chapter presents the conclusions drawn from this research organized by the research questions in the first section. The research is then evaluated in section 6.2. After the research evaluation, the limitations of the research results are discussed in section 6.3. An evaluation of the research impact is provided in section 6.4, where the academic and industrial impact are described separately. The closing words of this thesis are then provided in section 6.5 where suggestions for further research are given, based on the experiences from this research project.

6.1 Research findings

This research has aimed at answering the RQs through participation in a large scale technology platform development project—the DEAP project. The findings have been presented in papers and in this thesis. Here, conclusions on each of the RQs are presented in order.

6.1.1 Conclusions on research question 1

> **Research Question 1** How do the technology development activities and context during simultaneous product technology and production development affect architecture modelling in terms of what to model, what the model focus should be, and what goals should be supported by the models?

Results on the challenges and context of technology development have been presented from three perspectives—the general context, the challenges and application context within the DEAP project, and the context and challenges within the platform development in the

DEAP project. The conclusions on RQ 1 are drawn from reflections that span across all three perspectives and are here presented as three themes: Verification and validation of technology; Balancing commonality and uniqueness; and critical production capabilities.

6.1.1.1 Verification and validation of technology

Within a technology development context aiming at commercialization, validating the functionality, performance, and application feasibility represent key challenges to be overcome through the development activities. This entails identifying feasible applications and validating the technology within those applications. However, to be able to validate the feasibility of using the technology in applications, it's expected performance must first be verified internally.

Technology Prototypes capable of demonstrating a limited subset of the intended functionality can provide a means for identifying application match, understanding application requirements specific to the technology, and support identifying unique properties of the technology within the specific application. The availability of robust, functioning, prototypes for integration in an application context is imperative for both technology development and later commercialization efforts. Identifying and agreeing on the purpose of a Technology Prototype supports common expectations to the results to be obtained through Technology Prototype testing and to the functionality and performance of the technology component integrated into the Technology Prototype.

To reach a point where Technology Prototypes can be designed and constructed and to facilitate agreement on purpose, the technical solution space for the Product Technology Architecture must be investigated, determined, and communicated. Collaborating with application experts can support identification of application requirements and by linking these to product concepts and Product Technologies, an overview of the intended capabilities of the Product Technology Architecture can be acquired. Such an overview—especially if combined with a roadmap for development deliverables—can be valuable for identifying what can be integrated into Technology Prototypes within the scope of the technology development project. Product Technology performance can be very uncertain during technology development and changes can occur that alter the achievable performance or functionality—e.g. due to development paths taking an unforeseen turn. Inclusion of intended and achieved performance for both product concepts and Product Technologies on such an overview can assist in communication with collaborators on performance expectations and status of development.

Testing a technology in an application through a Technology Prototype does not only provide information on application feasibility and application requirements. Integration and testing a technology in an application context can shed light on challenges yet to be handled in technology development and identify faults in current Product Technology implementations. In this way, Technology Prototypes can provide input on critical development issues for both product concepts and Product Technologies.

6.1.1.2 Balancing commonality and demonstration of technology uniqueness

In a technology development project aimed at fulfilling a broad range of application requirements a balance must be struck between developing generic, flexible, Product Technologies that can be applied in a variety of applications and providing bespoke solutions to potential customers aimed at maximizing functionality and performance in an individual application. Technology development can be a resource intensive undertaking and developing tailored solutions for every potential application is probably not feasible—at least not when it is not yet clear what applications carry the greatest potential for successful commercialization. On the other hand, developing only generic solutions—a one-size-fits-all strategy—may present difficulties in investigating the potential performance in the individual applications and realizing the unique properties of the technology under development in each application.

Successfully carrying out such a balancing act depends on being aware of current and future capabilities in developing and constructing prototypes, of the impact on resource consumption of introducing performance or feature variants, and evaluating the value of tailoring solutions in each individual case.

6.1.1.3 Critical production capabilities

The ability to deliver robust, functioning, prototypes for integration in Technology Prototypes in application environments relies not only on development capabilities but also heavily on production capabilities. There are two sides to the importance of critical production capabilities: production quality and the ability to produce on an industrial scale. While optimal timing of implementation of production capabilities will vary from project to project and is not covered here, critical production capabilities must match the needs of the firm during technology development.

Developing production capabilities alongside technology development can be critical in reaching necessary production quality levels to produce robust prototypes. This may entail production capabilities either at a laboratory scale or a larger scale but acquiring a product quality level on a laboratory scale that is not reproducible on an industrial scale—or not economical—has limited value. However, if industrial production capabilities are implemented, these must be fitted to the needs and progress of technology development and leave sufficient flexibility to cope with changes in the development path taken. Critical production capabilities that are central in determining obtainable product quality in the context of the technology being developed and that are relevant to industrial scale production, do not only support production development and prototype production, but can also be central in proving to potential customers—and the firm itself—that the firm has the ability to produce quality products based on the technology in the required quantities.

Identification and implementation of critical production capabilities—that facilitate increased production quality and determination of the feasibility of industrial scale production—can support both technology development and technology diffusion. Implementation of critical production capabilities requires an overview of required capabilities and planning when to implement them.

6.1.2 Conclusions on research question 2

> **Research Question 2** How can a Product Technology Architecture be modelled during technology development as a way to structure the development of a foundation for multiple product platforms?

Papers D and E provide an answer to RQ2 through the Product Technology Architecture modelling framework. By defining and breaking down the architecture of a generic DEAP transducer on the basis of organs—acting as modelling elements for Product Technologies—the DEAP technology architecture could be defined from early on in a way that was able to continue capturing the Product Technology Architecture as the development project progressed.

For each generic organ in the Product Technology Architecture, a number of organ alternatives are defined—each providing a unique performance goal and functionality to the Product Technology Architecture. These organ alternatives provide a mapping of the technical solution space. The rationale for inclusion of the organ alternatives lies in their functionality and performance goals and their relational links to application concepts and requirements—the model thus communicates their role in the Product Technology Architecture. This mapping in an early version of the Product Technology Architecture model was used in the DEAP project to evaluate and choose generated product concepts and organ alternatives for inclusion in the Product Technology Architecture—thereby facilitating structuring the development of a foundation for multiple product platforms.

> **Supporting Research Question 2.1** What can be constituted as relevant modelling elements to be included in a Product Technology Architecture model during technology development, where the product and production architecture descriptions are not yet complete?

Those elements that are fit for inclusion in a Product Technology Architecture are those that can be isolated from individual applications while providing value to the Product Technology Architecture development. Individual parts and standard designs in the form of physical instances of modules and such are too directly aimed at individual applications to fit within a Product Technology Architecture and indicate completeness in definition that is unlikely to be in place during the development phase. With such elements, changes during development can be expected to cause changes to the Product Technology Architecture definition at short intervals and cause a loss of stability to the Product Technology Architecture definition.

However, without links to real applications of the technology inclusion the rationale for Product Technology components cannot be captured in the model. In the Product Technology Architecture modelling framework, the inclusion of the following modelling elements is proposed:

- Application requirements
- Application concepts
- Transducer requirements
- Transducer concepts
- Product Technology Architecture structure
- Product Technology alternatives in the form of organs

Inclusion of these elements—modelled at a detail level fitting to the development progress—provides an overview of the goals of the Product Technology Architecture in terms of application requirements fulfilment, the transducer concepts in which Product Technologies shall be integrated, and the Product Technologies to be developed. During the development, fulfilment of development goals in these dimensions can be monitored by updating data on achieved performance for Product Technologies and product concepts at a generic level and compared to the intended performance goals.

> **Supporting Research Question 2.2** How can the functional aspects of a product architecture be modelled during technology development in such a way that a Product Technology Architecture's capabilities can be discussed and communicated with stakeholder groups in support of the development of the Product Technology Architecture?

Functional aspects of a Product Technology platform relate the elements of the platform to its capabilities in products and applications. In the Product Technology Architecture, each Product Technology alternative is mapped through product concepts to application concepts and a range of application requirements. By 'reading' the Product Technology Architecture model right-to-left, it can be identified what functionality each Product Technology alternative brings to the table and by 'reading' it left-to-right it can be identified how each identified application's requirements are fulfilled by the Product Technology platform. The aim with this mapping is to capture and communicate the functional capabilities of the Product Technology platform. This provides a rationale for the inclusion of Product Technology elements and a frame for identifying and defining the necessary functionality of each Product Technology alternative.

Although mapped to applications in this way, each Product Technology alternative is decoupled from individual applications in the sense that no single application is a sole determinant for Product Technology functionality. Within the context of the uncertainty inherent in technology development—both technology and application—a broad perspective on application requirements and how to fulfil them is necessary. It is not certain, during technology development, in which applications the technology will provide the most value and therefore Product Technology development needs to be flexible enough to enable fulfilment of a wide variety of requirements—but still within boundaries that are small enough to enable effective technology development. On the other hand, as it is not certain either what the results of Product Technology development will be, the mapping needs to provide indications of the capabilities of each Product Technology alternative—to be able to identify the consequences of development difficulties on the capabilities of the platform. The mapping in the Product Technology Architecture aims to identify what functional capabilities each Product Technology alternative brings to the platform and what application requirement fulfilment is dependent on the Product Technology alternative development being successful.

> **Supporting Research Question 2.3** Through what mechanisms can architecture models support platform development in an early phase of simultaneous product technology and production development?

When used as a physical print-out during meetings—in the form of a large poster—the Product Technology Architecture model took the role of a boundary object (Star and Griesemer, 1989). The Product Technology Architecture poster facilitated dialogue internally in the platform development Work Package on the contents of the platform and on status and goals of individual development sub-tasks. As a boundary object, it also facilitated dialogue between heterogeneous stakeholder groups when platform development was being discussed with stakeholders outside the platform development Work Package. The use of e.g. Technology Readiness Level documents and architecture models to communicate with both internal and external stakeholders has been found to provide valuable support for effective communications in previous research (Bruun et al., 2014; Mankins, 2009).

The definition of the generic Product Technology Architecture through organs, provided a classification for sub-tasks within the platform development Work Package. The organ alternative overview functioned as an overview of the development tasks and during task definitions and reviews—supporting the organisation of the development. The organ alternative overview was used to facilitate discussions on task definitions and the links to both DEAP transducers and applications were used to support argumentation for decisions on the task definitions. At first, short tag-lines were used to indicate the role of each organ alternative and later on, relative performance parameters for each organ alternative and DEAP transducer were defined. These performance parameters included both an *intended* performance value—indicating the development goal—and an *achieved* performance value—indicating the performance that had been achieved in the development. These values provided a means for gaining an overview of the development progress towards performance goals across the Product Technology Architecture.

6.1.3 Conclusions on research question 3

> **Research Question 3** How can a Production Architecture be modelled in simultaneous Product Technology and production development to support development decisions regarding the production system architecture?

The Production Architecture modelling framework described in papers F and G presents a proposed solution for how a Production Architecture can be modelled within the context of technology development in support of development decisions. The case results describe how the Production Architecture models captured critical decisions regarding the production system development and communicated them to a heterogeneous group of stakeholders.

The papers also describe how the process of modelling the Production Architecture supported identification of and dialogue on critical production parameters. Figure 6.1 shows discussions during a DEAP Production Architecture modelling workshop. During the discussions on details of the production process in plenum in modelling workshops the draft Production Architecture models facilitated both discussions on details in the production process and a holistic overview of the production process—including its links to the capabilities of the Production Architecture to produce products based on the Product Technology Architecture.

The models provided a simplified version of the complex relationships between the production system's properties and characteristics, which facilitated the development team's exploration and communication of the production system—this is described as a benefit of system models in general in Albers and Wintergerst (2014).

> **Supporting Research Question 3.1** What can be constituted as relevant modelling elements to be included in a Production Architecture model in a technology development context, where the product and production architecture descriptions are not yet complete?

Figure 6.1: Details of the production system and development tasks were discussed during modelling workshops (Reproduced from paper F)

Paper G provides a literature based list of elements that should be included in a Production Architecture model in a technology development context in section 5.3.1. Through the listed elements, the structure, capabilities, and expansions to the Production Architecture can be modelled in a technology development context, as has been shown through the implementation in the DEAP project.

> **Supporting Research Question 3.2** How can the capabilities of a Production Architecture be modelled during technology development in such a way that they can be communicated and discussed with stakeholder groups in support of the development of the production architecture?

The Production Architecture modelling framework provides a proposal for how the capabilities of a production system can be modelled within a technology development context. In the Production Architecture modelling framework, the capabilities of the production system are modelled in terms of the product variants created—both what product variants are created and the product differentiation points—it's product and volume flexibility, and through indications of obtainable product quality. During the modelling of the Production Architecture's capabilities, it must be taken into account that information can be lacking during technology development, but it is nevertheless important to include those factors that represent known or envisioned capabilities of the Production Architecture to enable more qualified decisions to be made.

During technology development, accurate production costs are generally unavailable as neither the final production process nor the final products are completely defined—the focus in this context is on achieving the capability to produce products based on the new technology with sufficient quality and prove feasibility of high-volume production. Technology and application uncertainty make matters more complex than when developing a production system for a defined product family—which is why production flexibility modelling is important. Knowing what is being enabled and what the range of capabilities is, represents essential knowledge before implementing the Production Architecture.

To make decisions on the Production Architecture during development, it is imperative that the effect of those decisions on the capabilities of the Production Architecture to produce prototypes and—later on—products is identified. The capability modelling in the Production Architecture modelling framework includes the critical modelling elements needed to support the identification of the effect of decisions on those capabilities and communicating them to heterogeneous stakeholder groups.

> **Supporting Research Question 3.3** How can planned changes to the Production Architecture that are part of the planned development progress be taken into account in a model of the Production Architecture?

Modelling planned expansions or changes to the Production Architecture modelling framework is handled through the use of multiple modelling elements. For small changes, it may be fitting to show the current Production Architecture and it's planned expansions in a single model, for larger changes it is recommended to use multiple instances of the Production Architecture model. Each instance then corresponds to an instance of the Production Architecture at a particular moment in time. The latter approach is the one taken in the DEAP Production Architecture models and is similar to the approach commonly taken when modelling current and future state value stream maps (Braglia et al., 2006).

By modelling planned changes as full Production Architecture models, the changes to both the structure and the capabilities of the Production Architecture can be captured and identified. Following the modelling formalism decisions that have been identified as decisions to be made regarding expansions are explicitly highlighted. But as was seen in the case, decisions that have already been made are also modelled implicitly if they form part of the changes to the Production Architecture model and are captured by the modelling formalism. Such decisions can also be brought up for discussion with the support of the Production Architecture models through the inclusion of the changes to the structure and capabilities of the Production Architecture.

6.2 Evaluation of the research

6.2.1 Product Technology Architecture modelling framework

Papers C, D, and E are part of this evaluation as they cover the development, implementation, and evaluation of the same support: the Product Technology Architecture modelling framework.

Usability It can be argued that the usability of the Product Technology Architecture models has been proven through their use in countless meetings and the long-term use of the Product Technology Architecture models in the DEAP project. The models were used in meetings, hung on the wall in the production hall at Danfoss PolyPower, presented during project symposiums, and shown to external stakeholders visiting Danfoss PolyPower's offices. As the models were used to communicate the development to different stakeholder groups with success—as described in table 5.2—the usability criterion can be considered to be fulfilled.

Applicability The aim of the Product Technology Architecture modelling framework was to support the development of a foundation for future product platforms during technology development. The Product Technology Architecture models provide their support by modelling the contents of the Product Technology Architecture being developed in terms of technical solutions, product concepts and specifications, and application concepts and requirements. The models provide relational links between the purpose of future products and the Product Technologies being developed in the project. They furthermore facilitate a breakdown of a generic future product into Product Technologies through the use of organs and organ alternatives facilitate the organisation of development tasks based on required Product Technologies. The graphical format furthermore supports communication of the contents of the Product Technology Architecture and its development tasks to both internal and external stakeholders. On this basis, the Product Technology Architecture modelling framework is considered in fulfilment of the applicability criterion.

Usefulness The usefulness of the Product Technology Architecture modelling framework is evidenced by the extensive use of the Product Technology Architecture models in the DEAP project throughout the project. A bias factor may be identified as the lack of alternatives as it was the only overview of the Product Technology Architecture available in the project. However, feedback from project participants—acquired through interviews and casual conversations—indicates that the project participants found value in the Product Technology Architecture models as useful for communication and as a support tool for organising the Product Technology Architecture and making decisions during the development.

Observations also indicate that the Product Technology Architecture models became somewhat synonymous with the Product Technology Architecture—discussions on e.g. the capabilities of Product Technologies often referred to the Product Technology Architecture models to communicate what the Product Technologies were meant to achieve and how they fit into the development work in the DEAP project. This was especially apparent when discussions required the value perspective—what a Product Technology provided in terms of opportunities and value to potential customers.

6.2.2 Production Architecture modelling framework

Papers F and G are part of this evaluation as they cover development, implementation, and evaluation of the Production Architecture modelling framework.

Usability The Production Architecture modelling framework's usability was evaluated in paper G as the practicality of its use in the DEAP project. The construction of the DEAP Production Architecture models within a relatively short time period showed that the framework is practical to use within a limited time-frame. Feedback from project participants evaluating the Production Architecture framework implementation indicates that the framework is usable both from the perspective of the modelling task itself and the use of the models as communication tools with both internal—from the production development team—and external stakeholders. Observations of the use of the DEAP Production Architecture models in plenary sessions during a project symposiums support these statements. One point of critique was that detail levels could be overwhelming to some viewers, but this was considered a minor flaw and one that can be eliminated by removing particular detail levels for certain stakeholder groups. These results are taken as evidence for the fulfilment of the usability criterion.

Applicability Models based on the Production Architecture modelling framework describe the structure, capabilities, and expansion plans for a Production Architecture—which represents modelling elements based on literature on production systems with the context of technology development in mind. Decisions regarding the Production Architecture development and implementation of production equipment are dependant on an understanding of the effect of the decisions. Modelling the capabilities—in terms of product variants, potential production capacity, and indicative factors for obtainable product quality—for multiple instances of the Production Architecture provide not only an indication of the capabilities of the Production Architecture at one instance, but the changes to these capabilities as a result of development or equipment implementation decisions. On this basis, the applicability criterion is considered fulfilled.

Usefulness While it is difficult in a case study implementation to isolate the effects of a single tool, feedback and observations of the use of the DEAP Production Architecture models indicate that the models proved useful in the DEAP project. Feedback indicates that the models were used in conjunction with decisions on expansions to the DEAP Production Architecture and that they proved valuable due to their capture and communication of the structure, capabilities and the effects of expansions on these. The process of constructing the models facilitated identification of critical parameters that had previously not been known to the production development team as a whole and on a more general level the modelling process facilitated a unified view of the DEAP Production Architecture within the production development team. The models have been described as valuable during discussions on changes to the Production Architecture on the basis of both their detail level—facilitating identification and discussion on critical parameters affected by changes—and the overview provided by the models—indicating how changes in one part of the Production Architecture could affect other parts of the Production Architecture. Feedback and observations indicate furthermore that the models proved useful in communicating the DEAP Production Architecture to stakeholders outside the production development team. Therefore, the usefulness criterion is considered fulfilled.

6.2.3 Research on the context and activities in technology development

The thematic analysis of 138 monthly reports from the application Work Packages in the DEAP project was based on thematic coding. Team coding was applied in single sessions, but re-coding—which could have improved the intra-coder reliability—has not been applied. The data source—monthly reports from four Work Packages—can be considered a limiting factor. The data reflects the tasks and challenges reported by the Work Package leaders who authored the reports and their individual perspectives therefore affect what data is included. The background and corporate culture of the individual Work Package leader is likely to influence what is emphasized in the monthly report from each Work Package. For the purpose of the research in this PhD-project, the paper represents supplemental empirical data that clarifies the technology development context. For this purpose and as the results are supplemented by observations during active participation in the DEAP project, the results provided by the analysis are considered to provide valuable input to the context clarification.

The interviews comprise only few individuals and therefore cannot be said to be a representative sample for the breadth of stakeholders that can be identified in a technology development context. Therefore, no attempt is made to statistically analyse the findings. For their purpose, however, which was to provide insight from alternative perspectives, they are considered valuable as informants.

- The interviewees represent a broad and heterogeneous set of potential stakeholders.
- Each provides a perspective on new technologies or products based on new technologies that is different from the other interviewees.
- Each interviewee has a role that is relevant to new technology introduction or the introduction of transducers based on a new technology and provide a perspective on activities and challenges related to these subjects

The interviews are therefore argued to be a valid source of supplemental information on activities and challenges related to technology development in the context of this research.

6.2.3.1 Case study validity

The fulfilment of the four criteria presented in section 2.2 is central for arguing the validity of the DEAP project case results.

Construct validity The constructs used in the results of the DEAP project that have not been subject to verification using the Design Research Methodology framework are the challenges and activities encountered in the DEAP project. The results described in section 5.1 stem from interviews with internal and external parties, from coding of monthly reports and analysis of a myriad of case documents, and from active participation in the DEAP project supported by extensive note taking. These multiple data sources support the presented results and no discrepancies have been identified in relation to the constructs of this research. The description of the case as presented has furthermore been reviewed by case participants, who had no objections to the case description. On the grounds of the above factors, construct validity is considered fulfilled.

Internal validity Although internal validity is more of a concern in explanatory case studies (Yin, 2009), it warrants a short discussion. Some causal relations that are presented in the DEAP project results—e.g. dependency between technology development and production capabilities and that models have provided support. These causal relations are in focus in internal validity. This research is characterised by extensive use of qualitative data based on multiple data sources. As qualitative data supports the identification of causal relations (Voss et al., 2002) and the results have been supported by multiple data sources and participant confirmation, internal validity is considered fulfilled.

External validity The extent to which the findings of this research have been proven generalisable is limited and the research limitations on these grounds are discussed in section 6.3.

Reliability The research has been performed within an industrial technology development project, which in itself cannot be repeated. But repeatability of the case study results deals with documentation and the argumentation applied. The empirical data achieved through participation has been documented through note taking and in some cases supported by audio or video recordings. Supporting this data is a plethora of case documentation in the form of reports, minutes of meetings, and presentations. However, simply by entering the area of concern, an action researcher affects the area of concern in an irreversible manner. This is not lessened by the introduction of support in the form of the modelling frameworks described in this thesis. Nevertheless, it is argued here, that to the extent of which the actions of the researcher can be taken out of the equation—which is possible to a limited degree due to the sheer size of the DEAP project as a whole—the case study results should be reproducible on the grounds of the empirical data collected.

6.3 Limitations of results

6.3.1 Single case implementation

The results of this research are limited by the limited application—the supports developed have only been implemented and tested in one case. However, the supports were developed on a solid theoretical foundation and the results are in many ways in tune with other results where similar supports have been implemented in different situations in industry. Furthermore, the PhD project covers active participation for almost three years of a four year case project—which has provided opportunity for immersion in the case project. Nevertheless, the transferability of the developed supports is yet to be proven.

6.3.2 Unique area of concern

The area of concern in which the supports were implemented and for which they were developed can be considered a niche within product development. The majority of product development comprises incremental development projects—not projects where the degree of novelty is as great as in the case project. NPD projects aiming for completely new products or product families will usually have lower levels of novelty than the case in this project. However, technology development projects are performed in industry that rival, and may even exceed, the novelty level encountered in the case project. Literature contains examples where technology development is performed in parallel with production development in other industries where uncertainties regarding both the product and production architectures are a defining factor (Walsh, 2004) and where production processes for novel technologies are developed with the aim of determining obtainable quality and increased capacity (Galagan et al., 2011).

With an increasing level of competition, there is increasing pressure on firms to shorten time-to-market—a pressure that is not likely to be limited to stages after technology development. The need to be able to generate revenue from technology development investments as quickly as possible and to leverage costs incurred in technology development across a wide range of products is not unique to the case project. Neither is the need to develop production processes concurrently with product development in an early phase to determine obtainable product quality and implement production capabilities—both for this purpose and to be able to produce prototypes and demonstrators—at an early phase. Therefore, the uniqueness of the case in this project is not considered a destructive factor in its generalizability—although it may be considered a defining factor for the scope of its applicability.

6.3.3 Research method

By following an Action Research based approach and actively participating within the area of concern, passive observations of the influence of developed supports becomes all but impossible. However, the immersion into the case project provides opportunity for insights that would otherwise remain obscure for the researcher.

As the case study followed a four year project with rather unique characteristics, where knowledge was continually increased as the project progressed, defining a reliable point of reference to evaluate the effect of introducing architecture models to the case project would constitute a meaningless endeavour. The participants in a four year technology platform project will inevitably increase their understanding and knowledge regarding the technology platform as the project progresses—hence, the research cannot reliably use a point of reference to measure the value of the supports introduced in the case project. However, the framework for iterating between descriptive and prescriptive stages defined by the Design Research Methodology supported research rigour and provided evaluation criteria against which the validity of the architecture models could be measured.

The repeatability of this research can be questioned—the participants cannot go back to their knowledge levels at the start of the project. But the research has been performed using multiple data sources and supported by extensive note taking in order to ensure that the progressive increase of knowledge and the effects of the introduction of supports are well documented and the research conclusions well founded.

6.4 Evaluation of the research impact

6.4.1 Academic impact

The academic impact of this research is found in contributions to the following bodies of academic literature:

- Architecture modelling
- Theory of Domains
- Technology platforms
- Production modelling
- Technology development

6.4.1.1 Contribution to architecture modelling

Mature NPD development tools and approaches are not optimal for use within technology development. While architecture modelling implementations in mature NPD have been described in literature, no literature has been found that describes the implementation of architecture modelling supports during technology development.

The research results include the definition of two architecture modelling frameworks: the Product Technology Architecture and Production Architecture modelling frameworks. The frameworks were developed for use within a technology development context, which has previously not had considerable focus within architecture modelling literature.

The contribution of the Product Technology Architecture modelling framework lies—in addition to being an adaptation of architecture modelling to a technology development context—in its entity relation modelling approach to linking application requirements and concepts to Product Technologies during development. It represents an architecture modelling approach that has been adapted to and implemented in a technology development project in industry and for which evaluations indicate is applicable, usable, and useful.

The contribution of the Production Architecture modelling framework lies in the definition of a modelling framework that captures the structure, capabilities and expansions of a production system during development. The modelling framework can be viewed exclusively as a technology development support, but as the framework was essentially used to support a decision situation, the results can be transferred to other production system decision situations—although some adjustments may be necessary.

6.4.1.2 Contribution to the Theory of Domains

The application of organs to represent Product Technologies as components of a Product Technology Architecture constitutes a contribution to the Theory of Domains. The utilization of the organ as a representative for Product Technology components provided an abstraction from the concrete physical realization that provided development flexibility in the beginning but could continue to be relevant throughout the project as the organs became more completely defined through the development work. While organs have previously been utilized in product family architecture modelling—e.g. in Harlou (2006)—the use of organs to depict Product Technologies as elements in a Product Technology Architecture has not been reported in existing literature. This use supports the broad applicability of the organ as a construct within engineering design and expands the already extensive evidence for the practical use of the Theory of Domains.

6.4.1.3 Contribution to technology platforms

These research results extend currently limited literature on technology platforms to include modelling of Product Technology Architecture during development. The term technology platform has been defined in literature and recent contributions describe the use of e.g. a technology platform portal as a knowledge sharing database to share knowledge on existing technology use within a firm. This research is—to the best of the author's knowledge—the first contribution dealing directly with Product Technology Architecture modelling during technology development—thus, providing a description of the value of a Product Technology Architecture modelling framework as a support tool for the technology development effort.

6.4.1.4 Contribution to production modelling

This research constitutes a contribution to production modelling by defining a modelling framework that considers the Production Architecture during development as a phenomenon to be modelled through three perspectives: structure, capabilities, and expansions.

6.4.1.5 Contribution to technology development

In addition to the use of organs to define Product Technologies, and the Product Technology Architecture modelling framework, the research contributes to technology development literature empirical data from a technology development project in industry—expanding the empirical data on the context of technology development.

6.4.2 Industrial impact

This research's contribution is operational support for a firm's capture and communication of the acquired knowledge of the capabilities and contents of a product technology platform during development—obtaining an overview of the technology being developed, how the components of the technology—Product Technologies—affect technology capability, and how technology capability relates to the potential use of the technology in future product platforms. This knowledge supports identification of reusable elements of a technology—during technology development—and linking these to the applications of the technology.

The Product Technology Architecture modelling framework represents a modelling tool that can support the organisation and structuring of technology development into the development of technology components that combined provide a technical solution to identified needs in applications. The relational links between applications and technology components support identification of the goals and value of the individual technology components of the technology being developed.

The Production Architecture modelling framework presented in this research is an operational framework to model the production architecture during technology development to capture and communicate the structure, capabilities, and expansions of the production architecture—supporting decisions on what and when to implement capabilities and communicating what they enable within the technology development project.

6.5 Suggestions for further research

One of the limitations of this research is that the implementation is limited to one case study: the DEAP project. It is therefore natural for further research to include implementation in more cases. Testing the modelling frameworks on a broader scale—which could include other technical domains such as electronics and software—would constitute a more rigorous test of the value of the modelling frameworks. Testing in other countries and industries represents another valuable goal for further research.

Of particular value would be to implement the frameworks in a case where the development could be followed from a technology development stage up to and including commercialization of the results of the technology development. Such a project, however, would likely be a long-term research project—in light of how time consuming technology development can be.

Research on the application of the Product Technology Architecture modelling framework with existing technologies in a firm with active technology development represents what could be an immensely valuable contribution to technology platform development. The value—and need—of combining the Product Technology Architecture with other technology platform contributions could be investigated by following this research path.

Further implementation of the frameworks is—in any case—likely to lead to refinement of the modelling frameworks and an increase in their transferability. It is also likely that the boundaries of their value could be more accurately determined than has been done in this research.

Bibliography

Aalto, T. (2004). *Project Portfolio Management in Telecommunications R&D*. Lecture notes, s-72.124 product development of telecommunication systems, 23.3. 2004, Aalto University, Espoo, Finland.

Aalto, T., Martinsuo, M., and Artto, K. A. (2003). Project Portfolio Management in Telecommunications R&D. In *Handbook of product and service development in communication and information technology*, chapter 5, pages 99–147. Springer.

Albers, A. and Wintergerst, E. (2014). The Contact and Channel Approach (C&C2-A): Relating a System's Physical Structure to Its Functionality. In Chakrabarti, A. and Blessing, L. T. M., editors, *An anthology of theories and models of design: philosophy, approaches and empirical explorations*, chapter 8, pages 151–171. Springer London, London.

Alizon, F., Moon, S. K., Shooter, S. B., and Simpson, T. W. (2007). Three dimensional design structure matrix with cross-module and cross-interface analyses. In *ASME Design Engineering Technical Conferences, DETC2007 — 34510*, pages 941–948, Las Vegas, NV. ASME.

Andreasen, M. M. (1980). *Syntesemetoder på Systemgrundlag - Bidrag til en konstruktionsteori (English: Machine Design Methods based on a Systemic Approach)*. PhD thesis, Lund Institute of Technology.

Andreasen, M. M., Hansen, C. T., and Cash, P. (2015). *Conceptual Design*. Springer, Cham, Switzerland.

Andreasen, M. M., Howard, T. J., and Bruun, H. P. L. (2014). Domain Theory, its models and concepts. In Chakrabarti, A. and Blessing, L. T. M., editors, *An Anthology of Theories and Models of Design*, chapter 9, pages 173–195. Springer London, London.

Andreasen, M. M., Mortensen, N. H., and Harlou, U. (2004). Multi product development: New models and concepts. In *Proceedings of the 15th Symposium on Design for X*, pages 75–86.

Arthur, W. B. (2009). *The Nature of Technology: What It Is and How It Evolves*. Simon and Schuster.

Aunger, R. (2010). Types of technology. *Technological Forecasting and Social Change*, 77(5):762–782.

Berglund, F., Bergsjö, D., Högman, U., and Khadke, K. (2008). Platform strategies for a supplier in the aircraft engine industry. In *2008 ASME International Design Engineering Technical Conferences & Computers and Information Engineering Conference. New York USA, 3-6 August 2008*, pages 55–66, New York, NY. ASME.

Blessing, L. T. M. and Chakrabarti, A. (2009). *DRM, a design research methodology*. Springer London, London.

Boyle, T., Kumar, V., and Kumar, U. (2002). The implementation of manufacturing flexibility: a conceptual framework. In Ganjavi, O., editor, *Proceedings of the Annual Conference of the Administrative Sciences Association of Canada Production and Operations Management Division*, volume 23, pages 52–61, Winnipeg, Manitoba. I.H. Asper School of Business, The University of Manitoba.

Braglia, M., Carmignani, G., and Zammori, F. (2006). A new value stream mapping approach for complex production systems. *International Journal of Production Research*, 44(18-19):3929–3952.

Bruun, H. P. L. (2015). *PLM support to architecture based development*. PhD thesis, Technical University of Denmark.

Bruun, H. P. L., Mortensen, N. H., and Harlou, U. (2014). Interface diagram: Design tool for supporting the development of modularity in complex product systems. *Concurrent Engineering*, 22(1):62–76.

Buur, J. (1990). *A Theoretical Approach to Mechatronics Design*. PhD thesis, Technical University of Denmark.

Checkland, P. and Holwell, S. (1998). Action research: Its nature and validity. *Systemic Practice and Action Research*, 11(1):9–21.

Clausing, D. (1994). *Total quality development: a step-by-step guide to world class concurrent engineering*. ASME Press series on international advances in design productivity. ASME Press, New York, NY.

Coghlan, D. (2004). Action Research in the Academy : Why and Whither ? Reflections on the Changing Nature of Research. *The Irish Journal of Management*, 25(2):1–10.

Cooper, R. G. (2006). MANAGING TECHNOLOGY DEVELOPMENT PROJECTS. *Research Technology Management*, 49(6):23–31.

Corin-Stig, D. (2013). *Platform Thinking for Technology Management—Supporting Knowledge Reuse in Technology Development*. Licentiate thesis, Chalmers University of Technology.

Corin-Stig, D., Isaksson, O., Högman, U., and Bergsjö, D. (2015). TERA – An Assessment of Technology Reuse Feasibility. *Procedia Computer Science*, 44(730):507–516.

Coughlan, P. and Coghlan, D. (2002). Action research for operations management. *International Journal of Operations & Production Management*, 22(2):220–240.

Crawley, E., Week, O. L. D., Eppinger, S. D., Magee, C., Moses, J., Seering, W., Schindall, J., Wallace, D., and Whitney, D. (2004). The influence of architecture in engineering systems. In *Paper presented at the MIT Engineering Systems Symposium*, page 29. MIT Engineering Systems Division.

Eder, W. E. (1998). Design Modeling-A Design Science Approach (and Why Does Industry Not Use It?). *Journal of Engineering Design*, 9(4):355–371.

Eldred, E. W. and McGrath, M. E. (1997). Commercializing new technology I. *Research-Technology Management*, 40(1):41–48.

Eppinger, S. D. and Browning, T. R. (2012). *Design Structure Matrix Methods and Applications*. The MIT Press, Cambridge, Massachusetts.

Farooq, S. and O'Brien, C. (2012). A technology selection framework for integrating manufacturing within a supply chain. *International Journal of Production Research*, 50(11):2987–3010.

Ferreirinha, P., Grothe-Møller, T., and Hansen, C. T. (1990). TEKLA, a language for developing knowledge based design systems. In *Proceedings of ICED*, volume 90, pages 1058–1065.

Galagan, Y., de Vries, I. G., Langen, A. P., Andriessen, R., Verhees, W. J. H., Veenstra, S. C., and Kroon, J. M. (2011). Technology development for roll-to-roll production of organic photovoltaics. *Chemical Engineering and Processing: Process Intensification*, 50(5-6):454–461.

Hansen, C. B. (2013). Cooperating or conflicting values? In *11th Public Management Research Conference, June 20-22 2013*, pages 1–47, Madison, Wisconsin. Public Management Research Association.

Harlou, U. (2006). *Developing product families based on architectures*. PhD thesis, Technical University of Denmark, Kgs. Lyngby.

Högman, U. (2011). *Processes and platforms aligned with technology development - The perspective of a supplier in the aerospace industry*. PhD thesis, Chalmers University of Technology.

Hölttä, K. and Salonen, M. (2003). Comparing Three Different Modularity Methods. In *ASME 2003 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, pages 533–541.

Hölttä-Otto, K. (2005). *Modular product platform design*. Doctoral dissertation, Helsinki University of Technology.

Hölttä-Otto, K., Chiriac, N. A., Lysy, D., and Suh, E. S. (2014). Architectural Decomposition: The Role of Granularity and Decomposition Viewpoint. In Simpson, T. W., Jiao, J., Siddique, Z., and Hölttä-Otto, K., editors, *Advances in product family and product platform design*, chapter 9, pages 221–244. Springer, New York.

Hubka, V. and Eder, W. E. (1988). *Theory of Technical Systems - A total concept theory for engineering design*. Springer-Verlag, Berlin.

Inman, R. R., Blumenfeld, D. E., Huang, N., Li, J., and Li, J. (2013). Survey of recent advances on the interface between production system design and quality. *IIE Transactions*, 45(6):557–574.

Jain, A., Jain, P., Chan, F. T., and Singh, S. (2013). A review on manufacturing flexibility. *International Journal of Production Research*, 51(19):5946–5970.

Jepsen, A. D. (2015). *Architecture Descriptions- A contribution to Modeling of Production System architecture*. PhD thesis, Technical University of Denmark.

Jiao, J. R., Simpson, T., and Siddique, Z. (2007). Product family design and platform-based product development: a state-of-the-art review. *Journal of Intelligent Manufacturing*, 18(1):5–29.

Jiao, J. R. and Tseng, M. M. (2000). Fundamentals of product family architecture. *Integrated Manufacturing Systems*, 11(7):469–483.

Jiao, J. R., Zhang, L. L., and Pokharel, S. (2006). Process Platform and Production Configuration for Product Families. In Simpson, T. W., Siddique, Z., and Jiao, J. R., editors, *Product Platform and Product Family Design*, chapter 16, pages 377–402. Springer Science+Business Media, New York.

Johannesson, H. (2014). Emphasizing Reuse of Generic Assets Through Integrated Product and Production System Development Platforms. In Simpson, T. W., Jiao, J. R., Siddique, Z., and Hölttä-Otto, K., editors, *Advances in Product Family and Product Platform Design*, chapter 5, pages 119–146. Springer New York, New York, NY.

Kvist, M. (2009). *Product Family Assessment*. PhD thesis, Technical University of Denmark.

Levandowski, C. E., Corin-Stig, D., Bergsjo, D., Forslund, A., Högman, U., Soderberg, R., and Johannesson, H. (2012). An integrated approach to technology platform and product platform development. *Concurrent Engineering*, 21(1):65–83.

Mankins, J. C. (1995). Technology Readiness Levels. *White Paper April*, 6(2):5.

Mankins, J. C. (2009). Technology readiness assessments: A retrospective. *Acta Astronautica*, 65(9-10):1216–1223.

Martin, M. and Ishii, K. (2002). Design for variety: developing standardized and modularized product platform architectures. *Research in Engineering Design*, 13(4):213 – 235.

Matt, D. (2008). Template based production system design. *Journal of Manufacturing Technology Management*, 19(7):783–797.

Matta, A., Tolio, T., Karaesmen, F., and Dallery, Y. (2010). A new system architecture compared with conventional production system architectures. *International Journal of Production Research*, 38(17):4159–4169.

Meyer, M. H. and Lehnerd, A. P. (1997). *The Power of Product Platforms*. Free Press, New York, NY.

Mortensen, N. H. (1999). *Design Modelling in a Designer's Workbench: Contribution to a Design Language*. PhD thesis, Technical University of Denmark.

Mortensen, N. H., Harlou, U., and Haug, A. (2008). Improving decision making in the early phases of configuration projects. *International Journal of Industrial Engineering : Theory Applications and Practice*, 15(2):185–194.

Muffatto, M. (1999). Introducing a platform strategy in product development. *International Journal of Production Economics*, 61:145–153.

Nasiriyar, M. and Jolly, D. (2007). Technology platform exploitation: definition and research boundaries. In *16th International Conference on Management of Technology-IAMOT*.

Negahban, a., Yilmaz, L., and Nall, T. (2014). Managing production level in new product diffusion: an agent-based simulation approach. *International Journal of Production Research*, 52(17):4950–4966.

Olesen, J. (1992). *Concurrent development in manufacturing - based on dispositional mechanisms*. PhD thesis, Technical University of Denmark.

Pahl, G. and Beitz, W. (2007). *Engineering Design: A Systematic Approach*. Springer, London, 3rd edition.

Pedersen, R. (2010). *Product Platform Modeling: Contributions to the discipline of visual product platform modelling*. PhD thesis, Technical University of Denmark.

Pirmoradi, Z., Wang, G. G., and Simpson, T. W. (2014). A review of recent literature in product family design and platform-based product development. In Simpson, T. W., Jiao, J. R., Siddique, Z., and Hölttä-Otto, K., editors, *Advances in Product Family and Product Platform Design*, chapter 1, pages 1–46. Springer New York, New York, NY.

Rosenberg, N. (1996). Uncertainty and Technological Change. *The Mosaic of Economic Growth*, pages 334–353.

Russell, R. S. and Taylor III, B. W. (2011). *Operations management - International Student Version*. John Wiley & sons (Asia) Pte Ltd., Hoboken, NJ, 7th edition.

Rykiel, E. J. (1996). Testing ecological models: The meaning of validation. *Ecological Modelling*, 90(3):229–244.

Sanchez, R. (2000). Modular architectures, knowledge assets and organisational learning: new management processes for product creation. *International Journal of Technology Management*, 19(6):610–629.

Sanchez, R. (2004). Creating Modular Platforms for Strategic Flexibility. *Design management review*, 15(1):58–67.

Sanchez, R. and Collins, R. P. (2001). Competing - and Learning - in Modular Markets. *Long Range Planning*, 34:645–667.

Sawhney, M. S. (1998). Leveraged High-Variety Strategies : From Portfolio Thinking to Platform Thinking. *Journal of the Academy of Marketing Science*, 26(1):54–61.

Schatzberg, E. (2006). Technik Comes to America: Changing Meanings of Technology before 1930.

Schein, E. H. (1995). Process consultation, action research and clinical inquiry: are they the same? *Journal of Managerial Psychology*, 10(6):14–19.

Simpson, T., Maier, J., and Mistree, F. (2001). Product platform design: method and application. *Research in Engineering Design*, 13(1):2–22.

Skinner, W. (1985). *Manufacturing - The Formidable Competitive Weapon*. Wiley, New York.

Sosa, M. E., Eppinger, S. D., and Rowles, C. M. (2007). A Network Approach to Define Modularity of Components in Complex Products. *Journal of Mechanical Design*, 129(11):1118.

Sosa, M. E., Mihm, J., and Browning, T. R. (2011). Degree Distribution and Quality in Complex Engineered Systems. *Journal of Mechanical Design*, 133(10):101008–1–15.

Star, S. L. and Griesemer, J. R. (1989). Institutional ecology,translations' and boundary objects: Amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. *Social studies of science*, 19(3):387–420.

Stone, R. B. R., Wood, K. L. K., and Crawford, R. H. R. (2000). A heuristic method for identifying modules for product architectures. *Design studies*, 21:1–47.

Suh, N. P., Cochran, D. S., and Lima, P. C. (1998). Manufacturing System Design. *CIRP Annals - Manufacturing Technology*, 47:627–639.

Swink, M. (1999). Threats to new product manufacturability and the effects of development team integration processes. *Journal of Operations Management*, 17(6):691–709.

Taguchi, G., Chowdhury, S., and Wu, Y. (2004a). Quality Loss Function. In *Taguchi's Quality Engineering Handbook*, chapter 7, pages 170–179. John Wiley & Sons, Inc., Hoboken, NJ, USA.

Taguchi, G., Chowdhury, S., and Wu, Y. (2004b). Robust Technology Development. In *Taguchi's quality engineering handbook*, chapter 17, pages 352–376. John Wiley & Sons, Inc., Hoboken, NJ, USA.

Tatikonda, M. V. and Rosenthal, S. R. (2000). Technology novelty, project complexity, and product development project execution success: A deeper look at task uncertainty in product innovation. *IEEE Transactions on Engineering Management*, 47(1):74–87.

Thenent, N. E., Settanni, E., and Newnes, L. B. (2012). Know what you need to know: The role of technological knowledge in product service systems. *Proceedings of the ASME 2012 11th Biennial Conference on Engineering Systems Design and Analysis*, 44:1–12.

Tiihonen, J., Lehtonen, T., Soininen, T., Pulkkinen, A., Sulonen, R., and Riitahuhta, A. (1998). Modeling configurable product families. *4th WDK Workshop on Product Structuring*.

Torry-Smith, J. M. (2013). *Designing Mechatronic Products - Achieving Integration by Means of Modelling Dependencies*. PhD thesis, Technical University of Denmark.

Tryson, M., Kiil, H.-E., and Benslimane, M. (2009). Powerful tubular core free dielectric electro activate polymer (DEAP) PUSH actuator. In Bar-Cohen, Y. and Wallmersperger, T., editors, *Proceedings of SPIE Smart Structures and Materials + Nondestructive Evaluation and Health Monitoring (EAPAD)*, volume 7287, pages 72871F–72871F–11. SPIE.

Ulrich, K. T. (1995). The role of product architecture in the manufacturing firm. *Research policy*, 24(3):419–440.

Voss, C., Tsikriktsis, N., and Frohlich, M. (2002). Case research in operations management. *International Journal of Operations & Production Management*, 22(2):195–219.

Walsh, S. T. (2004). Roadmapping a disruptive technology: A case study The emerging microsystems and top-down nanosystems industry. *Technological Forecasting and Social Change*, 71(1-2):161–185.

Weber, C. (2014). Modelling Products and Product Development Based on Characteristics and Properties. In Chakrabarti, A. and Blessing, L. T. M., editors, *An anthology of theories and models of design: philosophy, approaches and empirical explorations*, chapter 16, pages 327—-352. Springer, London.

Yang, B. and Burns, N. (2003). Implications of postponement for the supply chain. *International Journal of Production Research*, 41(9):2075–2090.

Yin, R. K. (2009). *Case Study Research - Design and Methods*. Sage Publications, Inc., Thousand Oaks, CA, fourth edition.

Zhang, L. L. (2007). *Process platform-based production configuration for mass customization*. PhD thesis, Nanyang Technological University.

Zhang, L. L. and Jiao, J. R. (2013). A graph rewriting system for process platform planning. *Decision Support Systems*, 54(2):1174–1191.

Zhang, L. L., Jiao, J. R., and Helo, P. T. (2007). Process platform representation based on Unified Modelling Language.

APPENDIX A

Paper A

Tasks and challenges in prototype development with novel technology—an empirical study
Poul Martin Ravn, Tómas Vignir Guðlaugsson, Niels Henrik Mortensen

Presented at the 20th International Conference on Engineering Design (ICED15), Milan, Italy.

INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED15
27-30 JULY 2015, POLITECNICO DI MILANO, ITALY

TASKS AND CHALLENGES IN PROTOTYPE DEVELOPMENT WITH NOVEL TECHNOLOGY – AN EMPIRICAL STUDY

Ravn, Poul Martin; Guðlaugsson, Tómas Vignir; Mortensen, Niels Henrik
Technical University of Denmark, Denmark

Abstract

This paper presents a thematic analysis of 138 monthly reports from a joint industrial and academic project where multiple prototypes were developed based on the same technology. The analysis was based on tasks and challenges described in the reports by project managers over a period of three years. 17 task themes and 9 challenge themes were identified. It was found that test, implementation, and project management were prominent tasks. Familiarization with the technology was found to a very little degree, which was in opposition to literature. The main challenge was found to be system development. It was found that the predominant tasks and challenges are distributed over long periods of time, rather than in chunks linked to a specific development phase.

Keywords: Technology, Early design phases, Project management, Development tasks, Challenges

Contact:
Poul Martin Ravn
Technical University of Denmark
Mechanical Engineering
Denmark
pmrav@mek.dtu.dk

Please cite this paper as:
Surnames, Initials: *Title of paper*. In: Proceedings of the 20th International Conference on Engineering Design (ICED15), Vol. nn: Title of Volume, Milan, Italy, 27.-30.07.2015

1 INTRODUCTION

Application of novel technology is regarded as one of the ways that companies can keep ahead of their competitors (Baughn and Osborne, 1989; Iansiti, 1995). Technology developers can benefit from the knowledge of lead companies that implement the technology in pre-development phases, thus increasing the knowledge about the technology in use. In such a case, a multi-prototype development strategy can be chosen, where multiple prototypes are developed sequentially to test the technology in different performance areas.

Early inclusion of companies at an early stage of technology development can be obtained through the use of prototypes. This will allow the benefits and principles of integration into a product system to be investigated and facilitates familiarization with the technology. However, there are great uncertainties at such an early stage, both regarding technology performance and appropriate lead applications (Baughn and Osborne, 1989) as the technology is still under development.

The aim of this paper is to investigate the tasks and challenges in a technology development project, from the point of view of the product developer in a technology transfer setting. The specific setup is where technology developer and product developer work together in the development of a prototype displaying the benefits of the technology in a product from the portfolio of the product developer. In this particular context, the technology was introduced to product developer at a very early stage (TRL 2-3).

As part of a research program this paper seeks to answer the following research questions (RQ):

- RQ1: What are the development tasks and challenges when building prototypes with sub-systems based on novel, advanced technologies, concurrently with the technology being developed?
- RQ2: How does early test of a technology at low technology readiness level affect the tasks and challenges?
- RQ3: How are the tasks and challenges found distributed over time in the projects?

2 METHODOLOGY

The overall methodology used for this paper is illustrated in Figure 1. Previously identified tasks and challenges in two development settings were extracted from literature; product development and development of product prototypes with novel, advanced technology components. Data analysis of 138 monthly reports from an industry project was used to identify the tasks and challenges for four teams working with development of prototypes combining principles of an existing product and a novel technology.

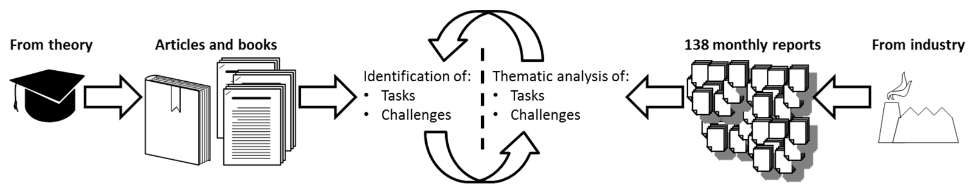


Figure 1. The research approach.

The monthly reports were used as part of the project reporting between the team managers and the overall project manager. The monthly reports covered the project from the time of initiation and three years into the project (august 2011 - October 2014). The reports specifically listed task progression and challenges for the respective months. The reports were analysed using thematic analysis (Braun and Clarke, 2006) with two coding cycles: one for initial summarization of data, and one for thematising. The task and challenge entries, as well as a list of theme definitions were given unique identifiers: PP-#, CH-#, and Co-#, respectively. A data handling record was used to document all steps. To increase reliability of the data coding, team coding was used; a second reviewer was assigned to review the entries in the first coding cycle (Miles et al., 2014). After this, code definitions were compared to create a unified coding scheme. Coding themes originated mainly from literature, but with inclusion of themes emerging from the analysed data as well. To discuss the findings, observations and meeting notes from the project period were used.

3 RELATED WORK

In this paper, two main terms are investigated, tasks and challenges. Tasks are understood as work underdone by engineers in a company, following work processes and procedures. Challenges are understood as areas that are identified to cause an additional effort to solve. This section will focus on tasks and challenges in two contexts; product development, and the development of prototypes with novel, advanced technologies. A distinction is made between regular product development, focused on the optimization of functionality and properties desired by a customer in a smart way (Mortensen, 2012), and early development of devices (prototypes) with novel technological principles applied more focused on exploring the benefits of the novel technology for possible exploitation (Iansiti, 1995; Nobelius, 2002).

3.1 Tasks and challenges in product development

Within the area of product development both tasks and challenges have been subjects of investigation as these are encountered every day in companies A general agreement on six general phases of design can be found: establishing a need, analysis of tasks, conceptual design, embodiment design, detailed design, and implementation (Howard et al., 2008). Each of the phases are often divided into smaller, well-defined tasks to enable concurrent work (Andreasen and Hein, 1987). Other tasks often found are documentation and specification as part of quality measures for the company, as well as what is produced (Pahl and Beitz, 2007).

In general, challenges for product development are represented by performance, schedule and cost (Mankins, 2009). When examining product development literature, subjects such as interfaces (Tomiyama et al., 2007), functions, properties, and structure are prominent (Pahl and Beitz, 2007; Ulrich, 1995). A literature study of previously reported challenges in mechatronic development indicated challenges within product, activity, mind-set, competence, organizational aspects, and other aspects (Morkeberg Torry-Smith, 2013). This indicates that challenges are found in multiple dimensions, and not only specifically target the product, but are also related to process and organization. Therefore, specific challenges will be extracted in the following section.

All together, the list of tasks and challenges in product development is inexhaustible, as each engineering domain will have each its tasks to undergo and challenges to solve. The following section will be used to draw out some of the expectations for what themes will be prominent.

3.2 Applying sub-systems based on novel technology

As complex products are not easy to decompose in order to allow new technology components to fit, a re-design may be needed. One approach is to scale down to prototypes, to a focused level where the combined system can be assessed (Ulrich and Eppinger, 2008). Uncertainty is often mentioned together with technology development (Rogers, 1995; Cooper, 2006; Mankins, 2009). The introduction of the technology element to the product system will result in challenges on more than one level. The general assumption in such a setup is that due to the already existing product design, some things may already be partly pre-defined, such as structure and properties. Therefore, it may be expected that the first general development phases will instead be focused on selecting and defining a match in a proper concept (Iansiti, 1995) as well as familiarization of the technology to break the habits connected with the replaced technology (Katz and Allen, 1985). For familiarization, the transfer of technology prerequisites an interaction between product development and technology development company as "People, not papers, transfer technology" (Foley, 1996). Understanding the technical issues of a technology before transferring it is found to be a challenge (Cohen et al., 1979).In the implementation phase, an emphasis can be expected on testing the prototype as functionality and desired properties need to be verified (Ullman, 2009). As two or more inter- or intra-organizational units are to interact, an agreement on resources, responsibility, differences in aims and ownership have been among the challenges reported by researchers focusing on supporting the process (Nobelius, 2002; Stock and Tatikonda, 2008; Larsson et al., 2006) Thus, project management can be expected to be a prominent factor (Iansiti, 1995).

3.3 Summary

The main tasks and challenges found in literature will serve as a guide for the analysis. Some of the tasks and challenges are expected to be increased when combining existing products and novel

technology in prototypes. Literature indicates that the occurrence of testing tasks should be expected to be high. Also, implementation and project management tasks are expected to be more frequent when integrating novel technology. As a separate task before or during the development process, familiarization should be a substantial part of the work with integrating the technology sub-system.
The technical development of the product is indicated to be a challenge due to the input of a novel technology.

4 INDUSTRIAL CONTEXT

A Danish 10 M€ project investigating, developing, and applying the Electro-Active Polymer (EAP) technology for transducer applications, has been used as a case for this paper. The project was divided into ten work packages (WPs). The WPs focused on the production as well as the product side of the technology (Sarban, 2013). The project was structured as a public-private partnership (PPP) project with multiple partners from industry and academia (I1-4, A1-3) (Hansen, 2013). Focus in this paper is on four WPs (denoted project 1-4) developing prototypes with the technology. For an overview of the projects, see Table 1.

Table 1. Overview of projects

	Project 1	Project 2	Project 3	Project 4
Application	Incremental motor principle	Energy harvesting device	Heating control valve	Loudspeaker
EAP tranducers used	3	1-4	1	2-4
Project partners	I1, A1	I1, I2, A2, A3	I1, I3, A1	I1, I4, A1, A3
Prototype iterations	2	3	3	3

In each of the projects, three sequential prototypes were planned. The data analysed were from the two first prototype iterations. The main difference between the projects was that in project 1, a principle, rather than a specific product was investigated. This meant that the prototype less comprehensive, compared to the other three projects. Project 1 was also initiated later than the other projects.
The project setups, following the PPP structure, had a virtual organization structure, here denoted the PPP shared setup.

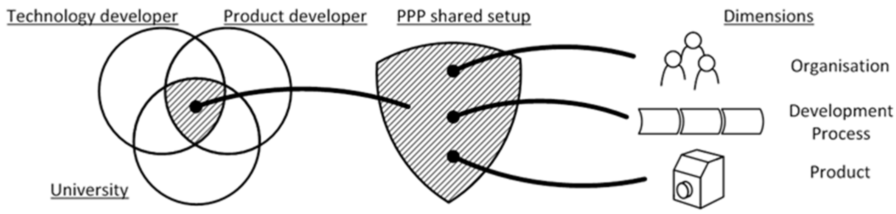


Figure 2. Project setup

The shared setup resources from each of the organizations were shared in a process to produce prototypes for demonstration and evaluation purposes, as illustrated in Figure 2.

5 FINDINGS

A total of 766 entries, from the 138 monthly reports were distributed as presented in Table 2.

Table 2. Overview of reports and distribution of entries in the four projects

Project	Project 1	Project 2	Project 3	Project 4	Total
# of monthly reports	30	39	31	38	138
# of task entries	68	257	117	98	540
# of challenge entries	30	100	58	38	226
Sum of entries	98	357	175	136	766

The entries were distributed with respect to tasks and challenges. The graphs are displayed with respect to the projects and the dimensions illustrated in Figure 2.

5.1 Tasks

All of the 540 task entries (100%) were used in the thematic analysis. As some entries represented multiple tasks a total of 683 task entries were identified. An abstraction adjustment of these, together with classification and collection resulted in 17 main themes. The themes were presented in Table 3 along with percent of total themes and theme description. The descriptions give an insight to the lower level themes found in coding cycle 1.

Table 3. Themes, percent and theme description for tasks.

Themes (Abbreviation)	%	Theme description
Test (TEST)	14,1	Test of systems or sub-systems developed within the projects.
Detailed design (DET-DES)	13,5	Detailed design activities.
Implementation (IMPL)	13,0	Constructing and installing the system or sub-systems
Project Management (PROJ-MAN)	11,4	Project definition, scoping, agreements, planning, and resource allocation activities,
Analysis (ANA)	8,3	Simulations, calculations and other tasks involving an analysis of system or sub-system performance
Conceptual design (CON-DES)	8,2	Concept design, brainstorms.
Problem (PROB)	7,5	Problems, failures, and repair activities
Documentation (DOC)	5,7	Documentation of system, test, or project progress.
Academic work (ACA-WOR)	4,0	Entries directly related to academic work, such as publishing and conferences, as well as preparations for these.
Specification (SPEC)	3,1	Specification of systems or sub-systems, current or future
Collaboration (COL)	2,9	Entries explicitly communicating sharing of knowledge and / or resources across project organisations
Procurement (PROC)	2,3	Finding, ordering, and purchasing parts or components from third parties.
Delay (DEL)	2,2	Delays in project due to various causes.
Review (REV)	2,0	Review of system or development activities.
Embodiment design (EMB-DES)	0,9	Embodiment design activities.
Limited Resources (LIM-RES)	0,7	Explicit entries on limited resources or limited progress due to limited resources
Familiarization (FAM)	0,1	Explicit familiarisation of project members with the technology and / or project.

According to Table 2, which lists the themes along with their proportional occurrence (across the four projects in total), themes relating to the building and testing of the prototypes are prominent for the projects It is also seen that many of the identified tasks from literature are represented.
Figure 3 shows the distribution of themes for each individual project to enable an analysis of common factors.
It was expected that TEST should be high, as well as PROJ-MAN. Common for the four projects was that they all had a representation of TEST as a prominent task e.g. among the top four for each project. It can also be seen that tasks related to constructing and installing (IMPL) is prominent in all four projects. This is an indication of the technology input to be affecting the development process.
In that relation the familiarization task (FAM) was also expected to be high. However, it occurs only once in a single project.

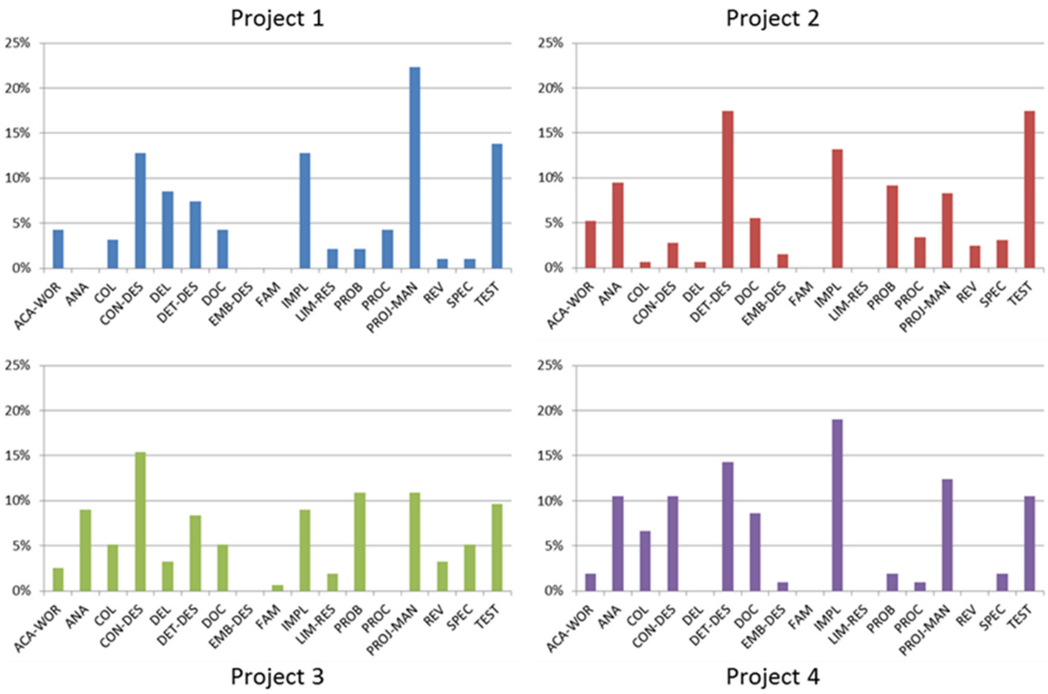


Figure 3. Tasks distributed on projects in percent

.

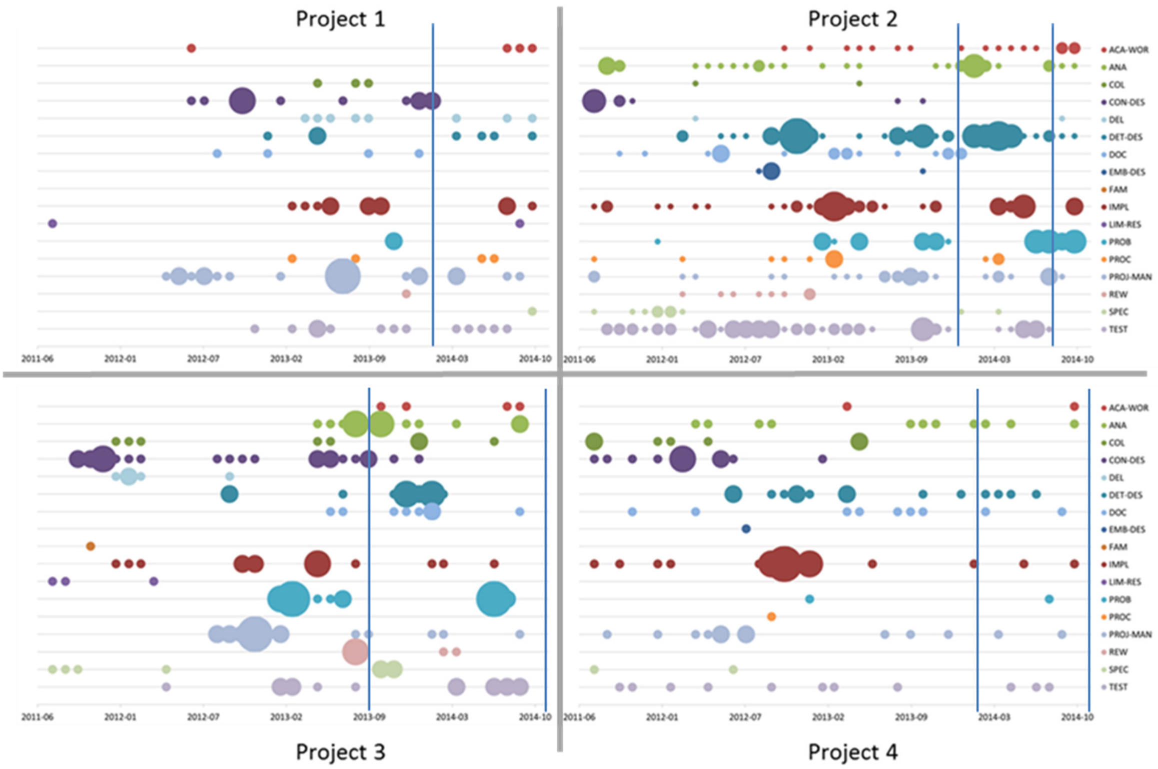


Figure 4. Task entries in the projects over time. Dot size indicates relative number of entries for each theme. Vertical lines indicate prototype completion milestones.

Figure 4 illustrates how the task entries were distributed over time in each project. Here, the number of entries related to a specific theme is correlated to the size of the dots. The larger the dot size, the more entries within the theme in that particular month. Project 1 was initiated later than the other projects, which can be seen from the lack of entries in the beginning of the figure.

As seen in Figure 4, most activities are distributed throughout the period in a greater extent than would be expected in product development projects with more mature technologies. Conceptual design (CON-DES) does occur most frequently at the early stages, but still occurs in all projects after detailed design (DET-DES) activities have been performed. Test (TEST) and implementation (IMPL) entries are seen regularly in most of the projects (see Figure 4), but Project 2 stands out with a high number of entries from an early stage. Problem (PROB) entries seem to occur close to test and implementation activities, which would also be expected in mature product development.

5.2 Challenges

Out of the 226 challenge entries, 202 (89.4%) of these indicated challenges in the four projects. Some of these entries represented multiple challenges, resulting in 251 challenges entries identified in total. Following the same procedure as with the tasks, nine main coding themes were identified. These are presented in Table 4.

Table 4. Themes, percent and theme description for challenges.

Code (abbreviation)	%	Code description
System development (SYS-DEV)	31,9	Challenges related to system development, including analysis, procurement, requirements, construction and testing the systems and sub-systems.
Limited resources (LIM-RES)	20,7	Limitations in personnel, equipment, financial or production capabilities, as well as time for activities.
Project planning (PRO-PLA)	14,7	Challenges related to planning of activities to ensure timely completion of project.
Resource allocation (RES-ALL)	11,6	Allocation of human, physical, or financial resources, including new positions within the project.
Robustness (ROB)	9,6	Issues with robustness of system or sub-systems, e.g. stability, failures, lifetime, and repairs.
Technology component production (TEC-PRO)	7,6	Production quality and production capability challenges.
Organizational support (ORG-SUP)	1,6	Limited support for the project within an organisation.
Technology development (TEC-DEV)	1,2	Challenges due to technology performance, e.g. core material composition and component performance.
Technology familiarization (TEC-FAM)	1,2	Resource use for familiarization with the technology.

Cost is not directly represented in Table 4 but can be seen through the theme LIM-RES. Again, these numbers are for the projects combined, and not for the individual projects. Figure 5 shows the proportional distribution of challenges for each of the four projects. The challenges identified can be organized after focus: Organisation, System and Technology. The organisational challenges cannot be said to be directly linked to development with novel technology. They may be a result of the collaborative setup presented in Figure 2. Therefore, a delimitation is made here; focus will be on system and technology, i.e. the five challenges indicated in Figure 5: ROB, SYS-DEV, TEC-DEV, TEC-FAM, and TEC-PRO. It can be seen that the projects 2-4 have a high occurrence of SYS-DEV. Project 1 on the other hand does not have any entries in the SYS-DEV theme.

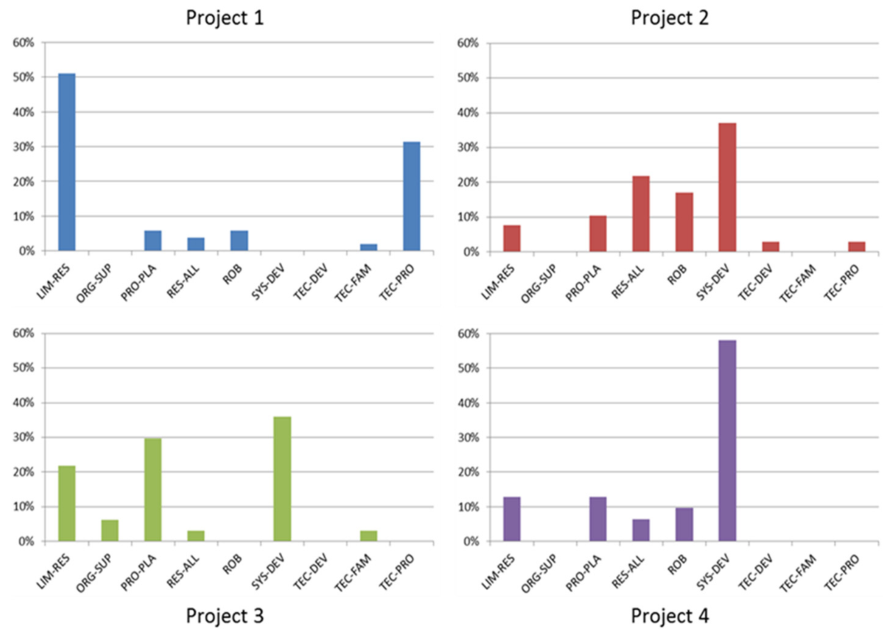


Figure 5. Challenges divided on projects in percent

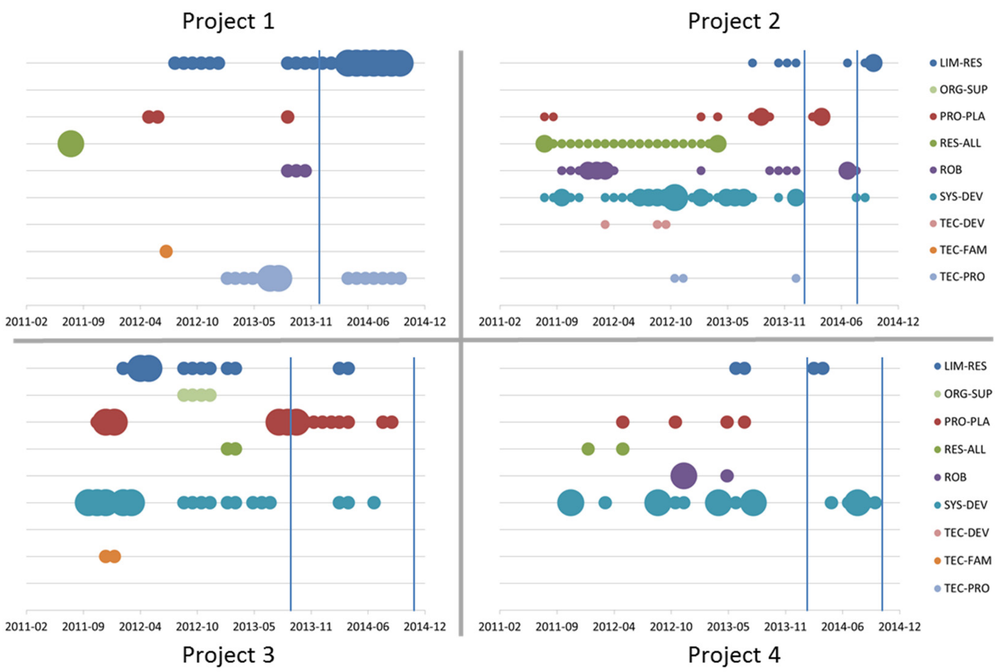


Figure 6. Challenges in the projects over time. Size of dots indicates relative number of entries within each theme. Vertical lines indicate prototype completion milestones.

While challenges are distributed throughout the period for all projects, as seen in Figure 6, there is little that obviously distinguishes the challenge distribution in the case projects from that which could be expected in more mature development projects. System development (SYS-DEV) challenges are present throughout almost the whole period for projects 2-4, but system development challenges can also be expected to occur, at least in some form, over most of the project period in mature product development. Technology component production (TEC-PRO) challenges are seen for a considerable amount of time in project 1, but production challenges can also hinder more mature product development.

6 DISCUSSION

Two main points will be discussed: the findings and study limitations.

6.1 The findings

The analysis revealed 17 task themes and 9 challenges themes. While a few prominent observations could be done regarding test, implementation, project management, and familiarization for the task themes, for challenge themes, only the system development challenge theme showed a clear similarity between the four projects. The rest of the identified themes either do not showing a tendency or as in the case with the challenges, cannot be directly linked to the development with novel technology.

That familiarization, expected to occur frequently in this setting, has not been found as a task theme reported on may be an indicator that it was either not done, or that it was not reported as a specific task.

It was expected that the SYS-DEV challenge would be high for the projects, but the big difference between projects 2-4 and project 1 was not expected. The main difference in the projects, as presented in the Industrial context section, was the application area, which may be the cause. Projects 2-4 were directly linked to industrial companies, whereas project 1 was used to explore an incremental motor principle - a considerably simpler system than those in the other projects.

To further investigate the correlation between the tasks noted by the project managers in the monthly reports and the time spent on the tasks a comparison with Gantt charts could be used. Looking at the distribution of entries shown in Figure 4 is can be seen that multiple entries can be made for a single month and it could also be seen that most of the themes were distributed over a longer period of time, compared to regular product development. Figure 6 however, revealed little to distinguish between the challenges in this context and a more mature product development.

In the industrial project, a prototyping with technology of low maturity level was tested. A comparison with a more mature technology would be interesting to map the differences between low maturity level and high maturity level, to find clear indications of the effect on the different themes.

6.2 Study limitations

Team coding (Miles et al., 2014), i.e. an additional researcher was used to analyse the data. This was done in order to strengthen the reliability of the analysis. In order to have better inter-coder reliability, the code definitions were discussed and decided upon for the second coding cycle. On the matter of intra-coder reliability the data has been aimed to be coded in focused, single sessions. A re-coding might have given higher intra-coder reliability (Miles et al., 2014). However, the data has not been re-coded for this paper.

Only one source of data has been analysed in this paper. In general, it may be discussed whether the data is a one-to-one representation of the tasks and challenges in the projects as only the comprehension of the team managers is represented through the monthly reports. The tasks and challenges noted in the monthly reports were filtered by the team managers' perspectives. Therefore, the dataset analysed is a representation of what the team managers normally report in their own organisation, and what they put emphasis on in that particular situation. Additionally, some tasks and challenges may have been met within the projects without being included. This means for the results, that they should be regarded as preliminary. For an extended study, additional sources of data should be combined for triangulation of findings. This would strengthen the validity of the findings.

7 CONCLUSION AND FURTHER WORK

In this paper empirical data of the tasks and challenges connected to development projects implementing novel technology has been extracted from 138 monthly reports from an industrial project over a three year timespan. A thematic analysis was performed to identify themes within the dataset.

Through the analysis of the data 17 task themes and 9 challenge themes were identified. When analysing the themes for each of the projects a number of similarities were seen. It was found the task themes test, implementation, and project management tasks had a high occurrence, which was expected. Based on literature it was expected to find technology familiarization tasks, however, only a single entry was found for the theme. For the challenges, a high occurrence of system development challenge was found which could indicate an effect from testing novel technology with low maturity level in product context at an early stage.

It was found that the predominant tasks and challenges are distributed over long periods of time, rather than in chunks linked to a specific development phase.

Further research could include utilization of additional sources of information. This would strengthen the analysis of a project of this type. Also, a more detailed analysis of the entries could provide valuable insight into the tasks and challenges encountered.

REFERENCES

Baughn, C.C. and Osborne, R.N. (1989) Strategies for successful technological development. The Journal of Technology Transfer, 14(3-4), pp.5–13.

Braun, V. and Clarke, V. (2006) Using thematic analysis in psychology. Qualitative Research in Psychology, 3(2), pp.77–101.

Cohen, H., Keller, S., Streeter, D. (1979) The Transfer of Technology From Research to Development, Research Management pp.11-17

Cooper, R.G. (2006) Managing technology development projects. Research-Technology Management, 49(6), pp.23 – 31.

Foley, J. (1996) Technology Transfer from University to Industry. Communications of the ACM, 39(9)

Griffith, T.L. (1999) Why New Technologies Fail. Industrial Management, 41(3).

Hansen, C.B. (2013) Cooperating or Conflicting Values? - A study of public and private values in public–private partnerships. In 11th Public Management Research Conference. Madison, Wisconsin.

Howard, T.J., Culley, S.J., Dekoninck, E. (2008) Describing the creative design process by the integration of engineering design and cognitive psychology literature. Design Studies, 29(2), pp.160–180.

Iansiti, M. (1995) Technology Development and Integration : An Empirical Study of the Interaction Between Applied Science and Product Development. IEEE Transactions on Engineering Management, 42(3), pp.259–269.

Katz, R. and Allen, T.J. (1985) Organizational Issues in the Introduction of New Technologies. Springer US

Larsson, M., Wall, A., Norström, C., Crnkovic I. (2006) Technology transfer: Why some succeed and some don't. In Proceedings of the 2006 international workshop on Software technology transfer in software engineering - TT ’06. New York, New York, USA: ACM Press, p. 23.

Mankins, J.C. (2009) Technology readiness assessments: A retrospective. Acta Astronautica, 65(9-10), pp.1216–1223.

Miles, M.B., Huberman, A.M., Saldaña, J. (2014) Qualitative Data Analysis A Methods Sourcebook. Third ed., Sage Publications, Inc.

Morkeberg Torry-Smith, J. (2013) Challenges in Designing Mechatronic Systems. Journal of Mechanical Design, 135(1).

Mortensen, N.H. (2012) Radikal Forenkling via Design, DTU Mekanik.

Andreasen, M.M., Hein, L. (1987) Integrated product development, IFS Publications Ltd.

Nobelius, D. (2002) Managing R&D Processes - Focusing on Technology Development, Product Development, and their Interplay. Chalmers University of Technology.

Pahl, G. and Beitz, W. (2007) Engineering Design: A Systematic Approach 3rd ed. K. Wallace & L. Blessing, (eds) London, UK: Springer-Verlag.

Rogers, E.M. (1995). Diffusion of Innovations, New York, The Free Press.

Sarban, R. and Guðlaugsson, T.V. (2013) Platform based design of EAP transducers in Danfoss PolyPower A/S. Proceedings of the SPIE - the International Society for Optical Engineering, 8687.

Stock, G.N. and Tatikonda, M.V. (2008) The joint influence of technology uncertainty and interorganizational interaction on external technology integration success. Journal of Operations Management, 26(1), pp.65–80.

Tomiyama, T., D'Amelio, V., Urbanic, J., ElMaraghy, W. (2007) Complexity of Multi-Disciplinary Design. CIRP Annals - Manufacturing Technology, 56(1), pp.185–188.

Ullman, D.G. (2009) The Mechanical Design Process, 4th ed., McGraw-Hill

Ulrich, K.T. (1995) The role of product architecture in the manufacturing firm. Research Policy, 24(3), pp.419 – 440.

Ulrich, K.T. and Eppinger, S.D. (2008) Product Design and Development. 4th ed., McGraw-Hill.

ACKNOWLEDGMENTS

The authors would like to thank the project participants. The work was financially supported by Innovation Fund Denmark.

APPENDIX B

Paper B

A multi-layered approach to product architecture modeling—Applied to technology prototypes
Poul Martin Ravn, Tómas Vignir Guðlaugsson, Niels Henrik Mortensen

Published (OnlineFirst) in Concurrent Engineering: Research and Applications:

Concurrent Engineering 1063293X15590843, first published on July 2, 2015
doi:10.1177/1063293X15590843.

Standard Article

Concurrent Engineering: Research and Applications
1–14

DOI: 10.1177/1063293X15590843
cer.sagepub.com
SAGE

A multi-layered approach to product architecture modeling: Applied to technology prototypes

Poul Martin Ravn, Tómas Vignir Gudlaugsson and Niels Henrik Mortensen

Abstract

Companies that wish to include novel technology in the product portfolio may need to test and evaluate the technology with the use of prototypes to learn its benefits. Without clear knowledge of the benefits of the technology to the products in the portfolio, in the form of increased performance, added functions, or material savings, the prototype development can be hard to manage. In this article, two contributions are made. The first adds to the vocabulary of prototyping, defining technology prototype, a prototype used for testing a novel technology in the context of an existing product. The second is a tool to model and manage technology prototypes: the Technology Prototype Product Architecture Tool (TePPAT). The TePPAT is a product architecture tool with three main sections: Purpose, Concept, and Architecture. The TePPAT was tested in four industry cases, all part of a public–private partnership project to support the development of technology prototypes using electro-active polymer transducer technology. The findings showed that the TePPAT supported the development teams in the four cases. It is concluded that the TePPAT can support multidisciplinary development teams in modeling and managing technology prototypes and can be correlated with improvements in the team collaboration, communication, and development performance.

Keywords

product architecture, architecture modeling, technology integration, technology prototypes, prototype development

Introduction

Developing new product capabilities will inevitably introduce challenges in achieving performance, schedule, and budget goals (Mankins, 2009). Technology development, regarded as more explorative than product development (Nobelius, 2002), can face bigger challenges in these three dimensions, as unknown aspects of an unexplored technology span multiple dimensions. From a product development point of view, the result of new technology development often means either completely new sub-systems or significantly changed sub-systems in the product, and both the technology developers and the recipients of the technology development face a number of uncertainties in integrating the technology into products. It has been shown that when developing systems incorporating novel technology, changes are not limited to single elements, but a multitude of other design elements that together make up the system (Henderson and Clark, 1990). Other studies have indicated that applying a system-focused approach, rather than an element-focused approach, supports aims of optimal performance (Tanner et al., 1989), higher development speed, and higher research and development (R&D) productivity (Iansiti, 1995). Some of these studies point in the direction of using product architecture modeling to overcome the increase of uncertainty in technology development projects.

Product architectures have a strong link to how companies design and manufacture products, for example, through development management, product change, or product performance, especially in R&D (Ulrich, 1995).

Section of Engineering Design and Product Development, Department of Mechanical Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark

Corresponding author:
Poul Martin Ravn, Section of Engineering Design and Product Development, Department of Mechanical Engineering, Technical University of Denmark, Produktionstorvet 426, 2800 Kgs. Lyngby, Denmark.
Email: pmrav@mek.dtu.dk

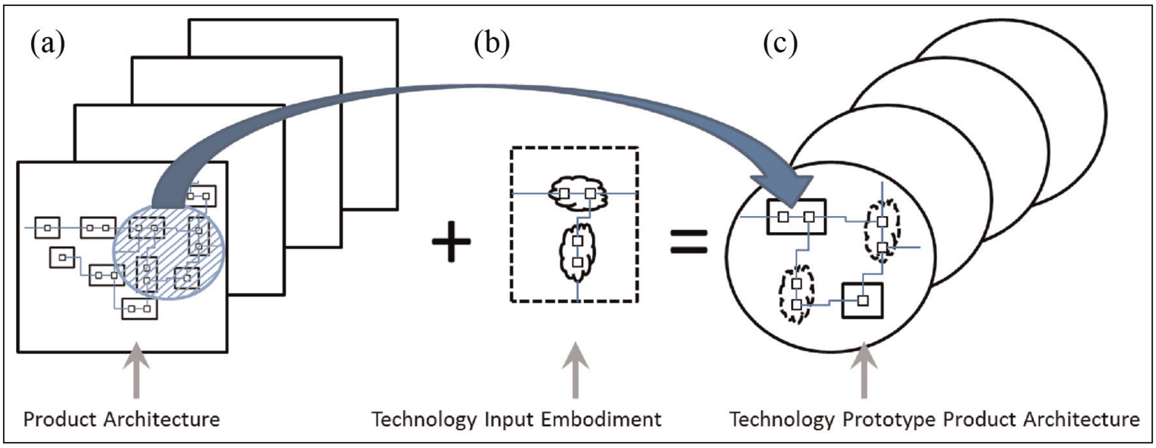


Figure 1. The pairing of (a) existing product or concept principles and (b) technology input into (c) technology prototypes. The technology prototype product architecture is a kind of product architecture. The focus in this article is on the technology prototypes and their product architectures.

This means that product architecture modeling may be a useful way to overcome the challenges of meeting performance, schedule, and budget goals. However, the predominant product architecture modeling approaches are mainly used in a more mature technology environment with a product as the end result. A focus on the use of product architecture modeling in a technology development environment where the end result for a project may be a technology prototype, rather than a product, has been lacking. In a technology development environment, the focus on the development of the technology itself leads to advancement in regard to function, properties, or performance in various dimensions, thus posing challenges to the development of such prototypes.

A technology development and evaluation project that was initiated in 2011 has targeted the commercialization of the novel electro-active polymer (EAP) transducer technology in a public–private partnership (PPP) (Hansen, 2013) project. One of many efforts toward commercialization was to develop a number of technology prototypes based on existing products estimated to be able to exploit the technology. The end product was envisioned as EAP transducers as a product sub-system, providing functionality and features to a product. The technology prototypes were built to demonstrate the integration and application of EAP transducers in different use and performance areas.

This article focuses on the modeling of product architectures in the development process of technology prototypes, demonstrating the use of a novel technology in an existing product or product concept. Using product architecture modeling makes it possible to analyze the product elements, their relations, and derived functions, in the technology prototypes. This article investigates the type of information that should be captured, and a modeling tool, the Technology Prototype Product Architecture Tool (TePPAT), is introduced. The TePPAT is used to collect and represent different types of information to describe the product architecture in multiple layers. The modeling addresses technology prototypes based on a combination of existing products and input from an emerging technology, as shown in Figure 1.

First, an introduction to the terms *product architecture* and *technology prototype* is provided, followed by a review of related work within product architecture modeling and the requirements for a modeling tool. Then, a description of the methodology is presented, followed by a description of the TePPAT modeling tool. The TePPAT was used in four industry projects and the findings from these are presented. Finally, the applicability of the modeling approach and the validity of the findings are discussed, and conclusions are drawn.

Product architectures and evaluation of emerging technology in products

As a result of many different understandings and definitions of *product architecture* and *prototypes*, the two will be defined here for clarification.

Product architecture

In system theories within the technical domain, products can be described through product structures. These are described as the sum of elements and their relation to each other, with a system boundary (Hubka and Eder, 1988). Based on a specific product structure, a product can deliver effects, both desired, for example, a holding effect, and undesired, for example, a noise effect. Andreasen et al. (1996) described a product as composed of multiple, superimposed, functional structure views from four basic classes: genetic, functional, product life, and product assortment. Functional structures are seen as the basis for product architectures, a term defined differently by different authors. Eppinger and Browning (2012) defined product architecture as a product structure that gives rise to a product's function and behavior. Ulrich (1995) defined product architecture as a scheme of how functions are allocated to physical components resulting in functional elements with relations, for a single product. Harlou (2006) defined architecture as a structure of a system constituted by standard designs and/or design units at three levels: product assortment, product family, and product. Design units may be functions, organs, parts, or an encapsulation of a group of these (Mortensen and Andreasen, 1996). Kvist (2010) stated that regardless of the perception of the term product architecture, these have to do with decomposition, arrangement, and interfaces. Standards, such as the ISO 42010 (Institute of Electrical and Electronics Engineers (IEEE), 2011), add an architecture viewpoint, framing a stakeholder's concern, such as purpose. Alvarez Cabrera et al. (2011) presented three goals of a product architecture model that enhance efficiency in the design of a product: provide overview, support integration, and provide traceability. Product architecture in this article combines the definition of Harlou and the goals from Cabrera: a structure of standard designs/design units that enhance efficiency in the design of a product by providing overview, supporting integration, and providing traceability.

Prototyping with novel technology input

There are two main understandings of the word prototype found in product development literature. The purpose of both is to gain insight into the intended functions and properties of the object being constructed, but in different phases of a product design. The first covers the whole range of design models used to gain insight into the functions and properties of the product being designed, (e.g. Ullman, 2009; Ulrich and Eppinger, 2008). The second is used to describe a specific type of design model used for instance to evaluate usage, function, reliability, and marketing properties, before a pre-production series (Buur and Andreasen, 1989). In this article, the former understanding of the word is used.

Prototypes can be used to investigate uncertainties regarding particular functions, properties, and performance, for example, of new solution principles or the introduction of technological abilities into a product. Traditional methods of manufacturing are often used in prototyping, but simulation and rapid prototyping, such as multiphysics simulation and three-dimensional (3D) printing, are also utilized. Prototypes can be broadly classified as physical or analytical (Ulrich and Eppinger, 2008). Physical prototypes are typically used to detect behavioral phenomena through real-world tests. Analytical prototypes, such as multiphysics simulations, allow for rapid exploration or prediction of the influence of various parameters. Although used for different purposes, the two types complement each other in development: analytical prototypes to predict results of physical tests and physical prototypes to verify results of simulations. Additionally, a classification of the degree to which the prototypes implement the functions of a product, focused or comprehensive, can be used (Ulrich and Eppinger, 2008). The focused prototype implements few or some functions, whereas the comprehensive includes an amount of functions closer to those of the actual product.

Artificial systems, such as products, serve a user's purpose (Hubka and Eder, 1988) and the use of prototypes in technical development is also driven by the engineer's purposes. These purposes can be learning, communication, integration, and milestones (Ulrich and Eppinger, 2008). According to Houde and Hill (1997), communicating the specific purpose of a prototype is essential as the prototypes themselves do not necessarily communicate their purpose to observers.

Ullman (2009) distinguished between four different types of prototypes: proof-of-concept, proof-of-product, proof-of-process, and proof-of-production. An alpha, beta, pre-production, and experimental or engineering prototype categorization links the prototype to the development process (Ulrich and Eppinger, 2008). These types and categorizations are very broad, which is why a more specific definition will be used in this article.

Prototypes developed to investigate and demonstrate the performance of a novel technology are, in this article, referred to as *technology prototypes*. These are a kind of experimental prototypes that demonstrate the principle of the use of a novel technology in part of an existing product. Technology is, in this article, regarded as the knowledge of scientific principles and the ability to apply these to produce an output from a technical system. In technology prototypes, it will often not be beneficial to implement all functions of the finished product, but rather to focus on implementing core functions, to which the novel technology provides a plausible solution to develop and test. The technology prototypes can be physical or analytical depending on the need. Technology prototype product architecture will in this case either consist of (a) part of an existing product architecture and an instance of the technology system (e.g. a prototype of a loudspeaker building on known product architecture, but with additions or changes hereto) or (b) a completely new architecture within that product field, made possible by the new technology (e.g. a prototype of a loudspeaker exploring new principles). This is referred to as radical innovation (Smith, 2010). The technology prototype product architecture is an instance of a product architecture (see Figure 1).

Summarizing product architecture and prototyping

Literature on product architecture and prototyping highlights some fundamental issues of importance for the situation being investigated in this article, that is, the testing and evaluation of novel technology to realize functions in a product. *Purpose* is of importance for both product architecture and prototypes as the purpose is the driver for building the technology prototypes. *Decomposition and composition* are of relevance as clearly defining the composition of a technology prototype can facilitate a clear indication of *where*, in the combination of existing product and novel technology, changes will be made to the design of the existing product. The *comprehensiveness* of the prototype affects the definition of the system boundary; communicating the comprehensiveness can aid in the definition of these boundaries and help maintain focus in developing the technology prototypes.

Related work

In this section, related work within the subject of product architecture models is described and argued in relation to modeling of the technology prototype product architectures. The section is concluded with the aims for such a model.

Product architecture models

Product architecture modeling is used to support product development in modern companies, and multiple approaches exist to model both individual product architectures and product family architectures. Product architecture models are based on a certain viewpoint of the product of interest (IEEE, 2011). These views may be visualized as diagrams, each describing the architecture in terms of a specific engineering discipline viewpoint, and therefore depicting the design solution from a specific perspective.

Function modeling is used to describe the desired functionality of a system (Pahl et al., 2007). A function structure is part of the analysis of the sub-functions and flow of, for example, material, data, and energy. Function modeling is a common approach in product development procedures to decompose a system into a functional hierarchy as a basis for targeting sub-solutions to sub-problems (Tjalve, 2003; Ulrich and Eppinger, 2008). Function heuristics are used for the definition of module-based product architectures (Otto and Wood, 1998; Stone et al., 1998). The Organ Diagram has been developed to depict functions and embodiment at an abstract level based on organs, that is, functional units seen as elements of a system (Andreasen et al., 2014). Organ diagrams are used for the definition of products, bridging function and structure (Ulrich, 1995). A Generic Organ Diagram (Harlou, 2006) has been developed to incorporate the depiction of product families together with the Product Family Master Plan (PFMP) (Harlou, 2006), illustrating generic design units of a product portfolio by using different views. The interface diagram (IFD) has targeted interfaces and the relation to product lifecycle management (PLM) systems (Bruun et al., 2014; Bruun and Mortensen, 2012), and the conceptual product platform (CPP) is used for the definition of a product platform early on in development projects (Gudlaugsson et al., 2014). The IFD distinguishes between a system view and a module view, which can be beneficial in the development of complex systems. Although the CPP is intended for use in early phases of development, it is focused on communicating the alternative variants of a product sub-component defined around a novel technology.

The design structure matrix (DSM) is a matrix approach used for modeling and identifying relationships between system entities (Steward, 1981). The DSM has been used to document architectures within product, organization, process, and multi-domains, and a combination of the former three (Browning, 2001; Eppinger and Browning, 2012). The DSM allows for control over and analysis of architectures through the study of interactions and interfaces among all of the elements in a system, and an analysis in graph theory, matrix mathematics, and specialized DSM analysis methods (Eppinger and Browning, 2012). The DSM3D has been used in module and variant creation (Alizon, 2007). Bonev et al. (2013) have combined the PFMP with DSM in the Product Requirements Development model to link and evaluate requirements.

Modular function deployment (MFD) (Erixon, 1998) is used to support the definition and evaluation of module concepts based on quality function deployment (QFD) analysis, thus aligning module proposals with customer requirements (Nilsson and Erixon, 1998). The alignment is supported through a Module Indication Matrix, in which module drivers and technical solutions are examined. The MFD facilitates reasoning about integration of multiple modules into one. While the MFD provides input for rational decisions on the modularization of a product, modules of the product are only represented in matrix form.

The A3 Overview is an approach that is used to collect, abstract, and present product architecture information in a way that can be understood and used by stakeholders (Bonnema et al., 2010). An A3 description of a system, composed of different view models, that is, a model-based description, a functional view, and a quantification of key parameters view, provides the information needed for developing an overview of the system (Borches, 2010). The A3 overview illustrates the principle of multiple view models to describe the product in a single overview to support communication, although an informal use guideline may result in overviews containing different models, dependent on the stakeholder. As models intended for other stakeholders should be finished in code understandable to those stakeholders (Buur and Andreasen, 1989), inconsistency may occur if or when the work is handed over to stakeholders using other types of models.

Common for most of these tools is that while they are purpose driven, they do not address the purpose of what should be built explicitly and few of them include working with modeling in different abstraction levels.

Conclusion on related work

The description of related work in the preceding section has presented different approaches for modeling and structuring/synthesis of both single-product architectures and product family architectures. Most of these are applied to support product development. However, most of the models aim to support the development of an end product, that is, a product that is offered on the market. They are not aimed at overcoming uncertainties present in technology development projects. Furthermore, the models do not propagate the specific purpose of the technology prototypes to support a joint goal of the development team. The models mainly support (a) the modeling of system elements and their relations and (b) clustering of these elements into modules in order to optimize the design of the product or product program. The models used in the definition of modules, for example, DSM and MFD, focus on the modeling of relationships between elements within the product being developed. The models are used in product development under the assumption that the product is known, more or less completely. As the technology prototypes are likely to be developed concurrently with the technology itself, not all elements of the technology prototype may be known or some may change as the technology advances. What is therefore not found in the literature is how to support the development of technology prototypes and a description of their product architectures.

The previous section showed that *purpose, comprehensiveness*, and *decomposition and composition* should be drivers for such a model. An information model for depicting technology prototype product architectures elaborates on these points. To allow for focused development and to make it possible to pinpoint the specific parameters of the technology that must be improved, a model of a technology prototype product architecture should also enable identification of where in the technology prototype the novel technology is specifically located. This facilitates differentiating the technology elements in the technology prototype from other elements in the prototype. In this way, performance parameters and focus areas for technology development can be targeted.

Methodology

The proposed model was developed and applied by means of iterations in a technology development project through an Action Research–based approach (Checkland and Holwell, 1998). The Case Studies were arranged as a multiple-case (holistic) design (Yin, 2009). An initial alpha version of the TePPAT was used to introduce the tool in four cases that were carried out in parallel, denoted Cases A–D. A total of 16 TePPATs were made in the cases. Feedback was used to revise and develop the tool and for improving and refining the results (see Figure 2). The sources of information were informal interviews, meeting notes from project participation, and participant observation. The latter two stem from active participation in the project work and the project meetings. The TePPAT has evolved through iterating between theoretical development of the tool and feedback suggestions, proposals, and experiences from meetings in the projects. It was expanded by revisions that afterwards were presented at meetings.

The cases were part of the same overall technology development and evaluation project, described in the "Introduction" section, with multiple collaboration partners from both industry and academia. The overall project was arranged as a virtual company (Chesbrough and Teece, 1996), sharing resources between the project partners. The development teams in the cases consisted of stakeholders from the collaboration partners: project managers, engineers, technology specialists, product specialists, professors, and PhD students. The team size of each project changed with the progress of the cases. The common denominator was the novel technology being applied in prototypes, but with a different product origin as a basis for

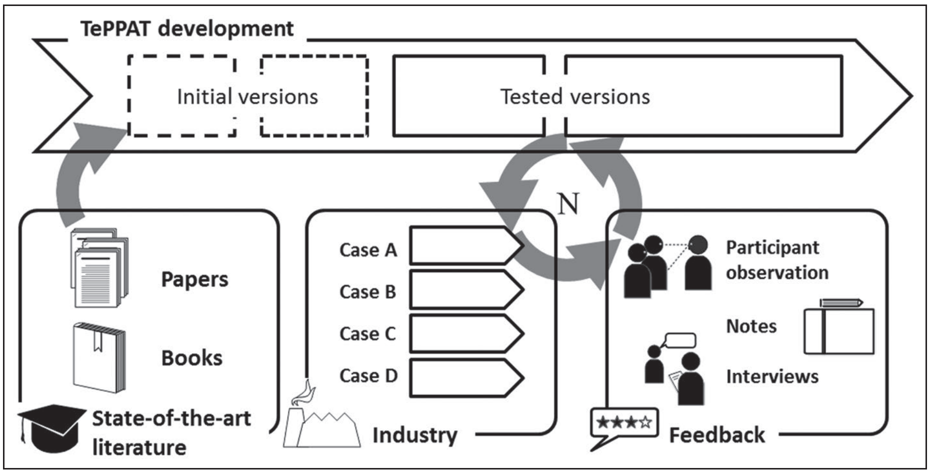


Figure 2. The development of the TePPAT. State-of-the-art literature formed the initial versions of the TePPAT. The TePPAT was tested iteratively (N) in four cases in industry and feedback was obtained through different means.

the cases. In the project, both large print-outs and electronic versions of the TePPAT were used.

The technology prototype product architecture tool

The tool presented in this article is a visual product architecture modeling tool. The term visual is in this work understood to mean a simplified graphical representation of the object being modeled, to support the development.

TePPAT model sections

The viewpoint of the model is to uncover the essence of the technology prototypes. This is described in three sections:

- The *Purpose* of the technology prototype, and quantified success criteria, specifying how the purpose will be achieved and quantifying the aims for the technology prototype.
- The *Concept* of the technology prototype is described by the main design units, as it is a composition of elements of the technology and part of an existing product principle.
- The *Architecture* of the technology prototype with elements and relations, and specific properties, capturing the system aspect by more than just the entities and relations. Specific information for the system, such as properties or other information linked to the prototype lifecycle, should be represented. Merely representing the structure will add little support to the development tasks.

The architecture section of the TePPAT is based on the Organ Diagram (Harlou, 2006) and has some commonalities with the IFD (Bruun et al., 2014). It is, however, targeted to meet the needs of the development teams within technology projects developing technology prototypes. The TePPAT is focused on the definition of a prototype's architecture and linked to information used in the development process, providing inputs to the refinement of the technology input. The TePPAT was developed and applied to support development of technology prototypes and capture information on the systems in which the technology is integrated and has not been tested in the development of commercial products. Utilization of the TePPAT in technology prototype development is intended to strengthen the development strategy and day-to-day work of a development team whose members belong to different domains and possibly different companies.

The modeling formalism

The three main sections *Purpose, Concept*, and *Architecture*, as illustrated in Figure 3, provide a structured description of the technology prototype of interest. Reading from the top down, the TePPAT will provide information on the purpose and goals of the system from the Purpose section, through the Concept section where the decomposed concept with success criteria for each sub-system is described, to the Architecture section illustrating the system architecture. The term "success criteria" is used in this context instead of requirements due to the context of technology prototyping. Here, requirements are often not fixed, but rather used as a guideline, a goal to achieve,

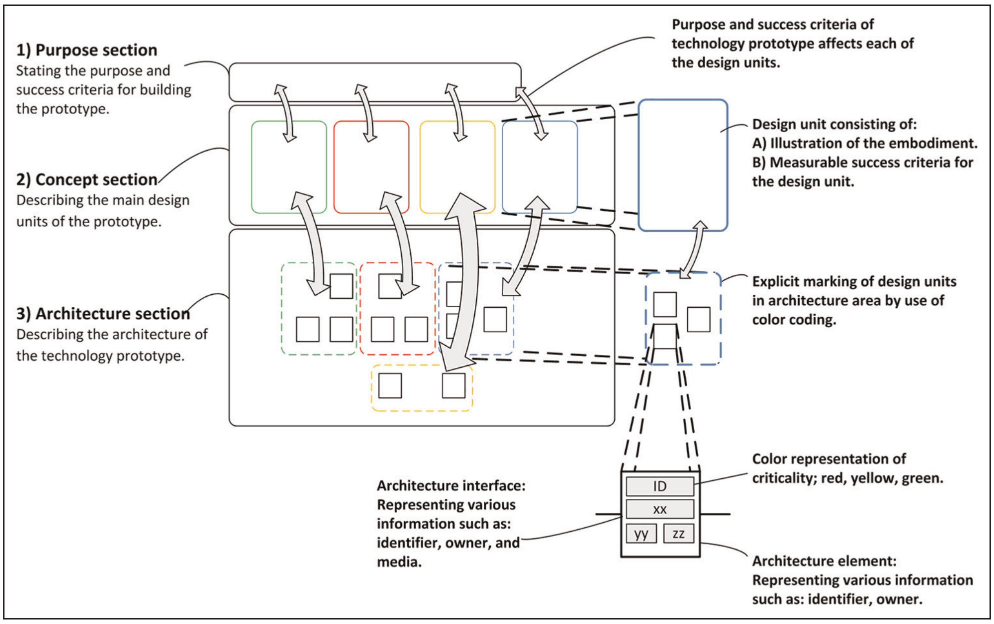


Figure 3. The three main sections of the TePPAT, (1)–(3), with the relations between them indicated by arrows.

or areas to be investigated, to learn about the technology prototypes. However, along with maturation of the technology, a transition to requirements may occur. The TePPAT is a tool intended to provide an overview of technology prototypes being developed—so the level of detail is on a system level and does not cover detailed design at the component level.

The *Purpose* section links the tool to the purpose of and reasoning behind developing the technology prototype. A definition of the purpose helps to delimit, or clarify, what the prototype should provide an insight into, based on the existing product or concept from which the prototype was derived. The purpose is based on knowledge of the existing product system, the solution principle that the novel technology shall replace, and the goals of and requirements for the prototype. Since the performance of the novel technology may not yet be equal to that of the solution principle it is to replace, the requirements are adjusted to realistic success criteria for the novel technology. It can be argued that if the purpose of the prototype cannot be stated, it should not be built.

The *Concept* section provides a description of the overall technology prototype concept and an abstracted decomposition of the technology prototype into subsystems: the design units. The rationale for such an abstraction is a definition of the main elements. This makes it possible to define success criteria for each of the main elements and to develop them concurrently. The decomposition in this section separates the technology element from the rest of the prototype. By separating the technology element, the development and learning points for each of the parts can be more easily targeted.

The *Architecture* section describes the product architecture of the technology prototype. The layout of the TePPAT should be based on a system perception of a technology prototype consisting of elements and their relations within a boundary defining what is “inside” and “outside” the product system (Hubka and Eder, 1988). The comprehensiveness of the technology prototype affects which elements are included and where the boundaries lie. The architecture is depicted through the use of functional elements and their relations. This provides a system overview. By reusing the decomposition made in the Concept section, in the Architecture section, sub-sections of the architecture are defined, and these provide a rational way of decomposing the technology prototype. The sub-system boundaries resulting from this decomposition are indicated by boxes with dashed lines to distinguish between interfaces to and from other sub-systems and interfaces within the sub-system. In situations where the sub-systems need to be modeled with increased detail, the sub-system boundaries will already be defined.

The functional elements contain additional information in fields, to encompass the need that stakeholders have of linking specific information to the system elements, for example, specific system properties. A criticality marking directs the focus on elements that need critical attention in the development or have not yet been developed. The lines drawn in the diagram

Table 1. Overview of Cases A–D.

	Case A	Case B	Case C	Case D
Application	Generic incremental motor principle	Wave energy harvesting device	Heating control valve	Loudspeaker
EAP transducer task	Actuator	Generator	Actuator	Actuator
Aim	Bi-directional incremental movement by use of multiple EAP transducers	Energy generation by mechanical stretching of EAP transducers	Flow control by actuation of radiator valve pin	Sound wave creation by variable actuation
EAP transducers used in technology prototypes	3	1–4	1	2–4
Actuation frequency range (Hz)	Medium (5–100)	Low (< 5)	Low (< 5)	High (100–4000)
Average power (W)	Medium (1–50)	High (10–1000)	Low (1)	Medium (1–50)
Prototype iterations	3	3	3	3
Project partners	I_1, A_1	I_1, I_2, A_2, A_3	I_1, I_3, A_1	I_1, I_4, A_1, A_3

EAP: electro-active polymer.

constitute the relation between the system elements. The interface can be one or more of the following types: material, energy, or information.

From a conceptualization viewpoint, the Concept section contains the two sides of a concept description (Hansen and Andreasen, 2002, 2003): the *idea with* and the *idea in*. The Purpose section describes the *idea with* on an abstracted level, while the Architecture section expands the details of the *idea in* the technology prototype. Thus, the relation between the Purpose section and the Concept section is a specification breakdown from the overall system-level purpose and success criteria to sub-system-level success criteria (Hansen, 1995). The relation between the Concept section and the Architecture section is the detail and concreteness. The relations between the sections are depicted as two-way in Figure 3. The rationale behind this is that discoveries made through test, simulation, or concept clarification may lead to insight into the technology prototype through *pop-up effect* or *pop-up incompatibility* (Hansen, 1995).

In the development of multiple subsequent technology prototypes, a time dimension is added to each instance of the technology architecture, dependent on the development strategy chosen. For a technology prototype, the relevant diagram can be used differently according to the chosen development strategy. If the strategy is to retain a specific technology prototype architecture design throughout the duration of the prototype iterations, scaling principles may be explored by projecting TePPATs for prototypes yet to be built. If different concepts are explored, the TePPAT can provide input to map the solution space of the technology architecture system through extraction of information such as system properties, system elements, and their relations.

TePPAT industry example

An industry example of the TePPAT is now presented to illustrate how the model has been implemented and used.

Case background

By aiming for commercial production of EAP transducers (Kiil and Benslimane, 2009), Danfoss PolyPower had set the goal of successfully introducing a novel technical alternative to linear electric motors to the market. Testing of the technology in different applications was underway in a large-scale PPP (Hansen, 2013), a development project with multiple industrial and academic partners (partners $I_{1–4}$ and $A_{1–3}$), supported by the Innovation Fund Denmark (IFDen). In this project, four sub-projects (Cases A–D) were working on integrating EAP transducers in multiple, very different technology prototypes. This resulted in different requirements as well as uncertainties for the EAP transducers in terms of geometry, interfaces, and functionality. For an overview of the cases, see Table 1.

Applying the TePPAT

The TePPAT was developed and applied to support the development of technology prototypes, further develop a platform definition of the technology system, and to provide valuable input from an application of the EAP elements.

The TePPAT was developed due to a clear need for a tool that provided the development team with a clear, common overview from the prototype system purpose to sub-system requirements and product architecture design. As the project progressed, the TePPAT was

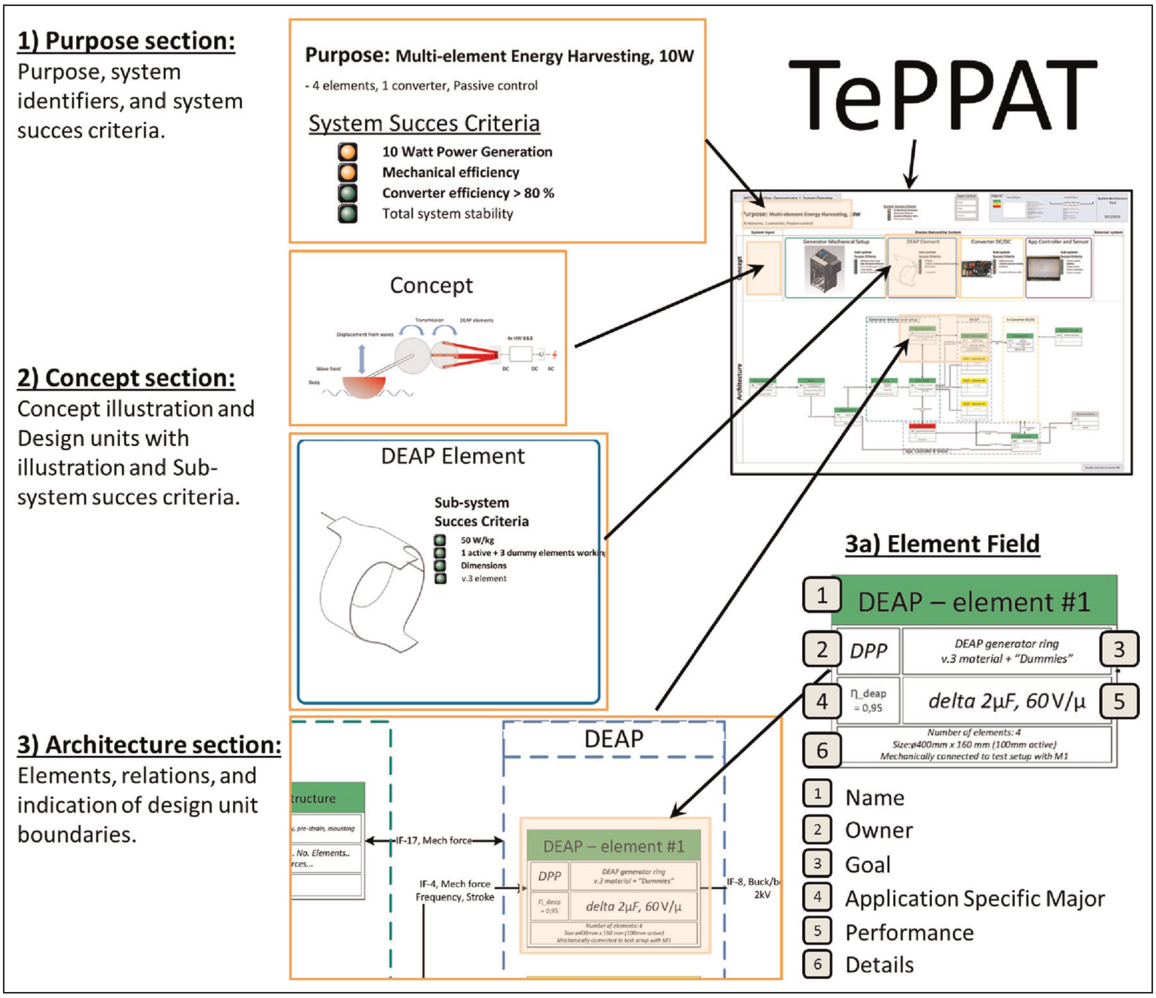


Figure 4. A TePPAT example from the IFDen project with highlights of the Main Sections (1)–(3).

continuously revised and refined to meet the needs of the project teams. Each of the prototypes had a corresponding TePPAT modeled in Microsoft® Visio®. The TePPAT representations were all within the same template, that is, the modeling formalism, but they allowed for the stakeholders to decide the content to a certain extent. A TePPAT example from Case B is shown in Figure 4.

The purpose description

In the Purpose section, the purpose of the technology prototypes was stated, for example, "Multi-element Energy Harvesting," together with a number of key system features, for example, "4 elements, 1 converter, passive control" as seen in Figure 4 for Case B. Overall system success criteria were formulated in cooperation with the stakeholders. Color-coded fields were used to make it possible to track and evaluate fulfillment of the success criteria.

The concept description

In the Concept section, the specific decomposition of the technology prototype into sub-system building blocks, or design units, was depicted along with illustrations for each of these. The illustrations were created by different means, for example, hand sketches, photos, and 3D computer-aided design (CAD) renderings, but with the same aim: to give a clear and logical breakdown of the system into its main building blocks. Specific success criteria for each of the different decomposition areas were stated along with indicators showing whether success criteria had been fulfilled, by use of color codes.

The architecture description

The architecture of each of the technology prototypes was depicted in the corresponding TePPATs with functional elements and relations. The sum of these corresponded to the defined comprehensiveness of the technology prototype. Within each functional element, the following fields were defined:

Name—which provides an identifier of the element. The background color in the name field, indicating element completeness and/or criticality, was used to link the architecture to the development process, and to indicate what was inside and outside the system boundary.
Owner—the responsible project organization or person.
Goal—the desired result for the element.
Performance—how well the elements perform on a number of parameters.
Application specific major—an application-specific parameter of special interest, for example, the power efficiency of an element.
Details—data field with information specific to the element provided for specific stakeholders to see, which would be too specific or irrelevant for some stakeholders.

For the element relations, lines were denoted with numbers for identification, owner, and the type of relation. The effect flow of the element relations, often bi-directional, was indicated by arrows.

In an initial version of the TePPAT, the architecture elements in the Architecture section contained multiple data fields, for example, status of the development task. This particular field was found to be redundant, as task status was already controlled by Gantt charts. In one case, the team reported the need for linking a specific data parameter to the elements, an efficiency ratio (η), as this was a main concern in that particular case.

Control of views

Based on a need in the project to communicate the technology prototype design in the development teams as well as upper management, the possibility of selecting specific views on the architecture was implemented. Control of visibility of views was made possible with coding of layers through Microsoft® Visual Basic® for Applications. The elements on the sheet were assigned to a specific layer: "Overview", "Detailed", or "Macro boxes." The "Overview" layer, by default always visible, contained all but the information in the *Details* field. The "Detailed" layer included the information in the *Details* field. "Macro boxes" were used to illustrate the specific decomposition of the system and were equivalent to the design units in the Concept section.

Filling out the TePPATs

In general, the pattern of use of the TePPAT was often started by first filling out the purpose, through the concept, down to the architecture. In the progression of the projects, additional details of the TePPATs were added in an iterative manner, following the understanding obtained during the maturation of the technology prototypes. Details were added in the timespan from early concepts, building, testing, and reporting, to new prototype iterations. TePPATs were filled out in both physical and electronic formats. Electronic format was used in WebEx meetings to create on-the-fly changes. Printed versions were used to allow the many stakeholders to collaboratively work with and update the prototype description by noting comments and changes directly onto the posters, followed by an electronic update. Follow-up reviews with multiple stakeholders within each project were completed to ensure common understanding and agreement on the design.

In some projects, a more detailed view was needed to support discussions on sub-systems. Therefore, a design unit would be expanded into its own sub-TePPAT.

Results from applying the TePPAT in the project cases

The results from applying the TePPAT in the cases are reported here with regard to the use of the TePPAT and the effects from using the TePPAT. The results are presented in Table 2.

The results were obtained from making a number of TePPATs to model physical and analytical technology prototypes in the cases. The TePPAT was used in a number of activities as a working document in both physical and electronic versions. Especially in the work with the definition of technology prototypes, a single page overview has been reported by stakeholders as an advantage of the TePPAT. The use of the TePPAT can be roughly divided into the following categories: reasoning why, defining the technology prototype, communication, and analyses. The effects from using the TePPAT ranged from better knowledge about the technology prototypes, aligning and strengthening the communication, to saving on technology prototype costs.

The observations of the teams using the TePPAT to plan ahead indicated that the teams needed clarification of details in consecutive technology prototypes. Using the TePPATs to supplement roadmaps and detailed design helped the stakeholders to define tasks and anticipate workload up front and to be able to carry these out in a concurrent manner.

Although the TePPAT modeling formalism was the same in Cases A–D, different ways of using the tool were observed in different cases. In Cases A–C, it was used on a regular basis during meetings, whereas in Case D, it was used less often. Despite being used less often in Case D, the team was observed to need the least guidance for using the TePPAT, or for using it to

Table 2. Usage and effects in the cases.

Topic	Usage	Effect	Cases
Reasoning why	Defining a shared understanding of the technology prototype	Avoiding misunderstandings by aligning the modeling language between the stakeholders from different engineering domains	A, B, C, D
	Active usage of Purpose, Concept, and Architecture sections during meetings	Overview of the technology prototype designs Agreement on shared description of technology prototype	A, B, C, D
Definition of the technology prototype	Defining purpose	Keeping the overview during development work Keeping a steady course in the development for defining when the prototype was finished and what the level of success was	A, B, C, D
	Defining concept	Defining of the responsibilities on a general level between the teams and the main interfaces	A, B, C, D
	Defining architecture	Increasing common overview for the development team	A, B, C, D
	Defining development tasks	Supporting the project management	A, B, C, D
	Identification of interfaces, elements, and functions of the technology prototypes	Pin-pointing the key interfaces and functionalities from introducing the novel technology	A, B, C, D
	Agreeing on interfaces	Enabling resource savings Avoiding confusion	A, B, C
	Abstracting detailed, technical discussions during meetings	Enabling different engineering domains to understand each other	A, B, C, D
	Defining system and sub-system tests	Enabling verification of system and sub-system tests	B, C
	Comparison of sub-system alternatives	Clarifying system composition	A
Communication	Communication of the technology prototype designs from an abstracted system level and down into details within each functional element	Strengthening communication and discussions internally in the teams by allowing pinpointing of discussion objects	A, B, C, D
	Communication to the upper management of the project regarding strategy planning and progression of the technology prototypes	Strengthening external communication of the technology prototypes by allowing an abstracted and coherent overview of the technology prototypes	A, B, C, D
Analyses	Iteratively modeling future instances of the technology prototypes ahead of building them in addition to roadmaps	Reducing the development cost of consecutive technology prototypes by indication of what elements could be reused Increasing visibility of development strategy	A, B
	Performing gap analysis	Guiding discussions	B, C
	Live update from purpose to architecture in a single view	Increasing meeting efficiency by allowing on-the-fly changes during meeting	A, B, C, D

communicate the technology prototype design to project partners.

In the cases, the TePPAT description became a living document in the sense that not only would detail increase over time as knowledge was gained on the development of the technology prototypes but the description would also change depending on the progress of the concurrent development of the core technology.

Discussion

In this section, the results are discussed along with the use of cases in the research. The findings reported in this article support findings from other studies (Alabastro et al., 1995; Bruun et al., 2014; Gebhardt et al., 2014) that visual architecture modeling is a powerful means of supporting and driving the development process by affecting both the communication and decision making in a positive way. Using it in both physical and electronic versions expanded the use of the tool beyond being the property of a single person and encouraged participants in meetings to discuss and make the changes needed directly into the TePPAT.

As the purposes of prototypes can be learning, communication, integration, and milestones (Ulrich and Eppinger, 2008), the findings from the cases can be argued to strengthen these purposes. The three sections, combined in the TePPAT, have also shown the worth of allowing abstraction and detailing in a single overview.

Whereas other tools are used for different system views, the TePPAT is used in a multi-layered approach at three levels: purpose, concept, and architecture. Three dimensions add to the multi-layered aspect, the first being the linking of purpose, concept, and architecture descriptions in the TePPAT; the second being the layers used in the architecture section, and the third being the time dimension.

The case construction for this article followed a multiple-case design, testing the use of the TePPAT. The strength of the cases was the shared context, that is, the integration of the same novel technology into concurrent technology prototypes for different projects. This allowed multiple cases of analysis to be used to test the repeatability of the use of the TePPAT, giving a more robust overall study (Herriott and Firestone, 1983). A shortcoming has been the limited number of cases. More cases are required to support the observations and effects of using the TePPAT through repeatability. The results presented from the case studies have mainly been qualitative, based on participant observation, meeting notes, and informal interviews. These sources of data made it possible to cover events in real time and provided insight into behavior (Yin, 2009). Further quantitative measures would provide a stronger indication of the effects of using the TePPAT. However, two things complicated the collection of such data: the project was still ongoing and there were few cases for comparison.

Conclusion

In this article, two main contributions are made. The first is to the vocabulary of prototyping, by the introduction of the term *technology prototypes*, covering prototypes developed to investigate and demonstrate the performance of a novel technology. The second is to the modeling and management of technology prototypes by the introduction of the *TePPAT*.

The TePPAT provided support for the development of technology prototypes in a Danish PPP technology test and evaluation project where the application of a novel technology was tested in multiple, heterogeneous instances. The industrial implementation in the IFDen project cases indicated the usefulness and effects of the TePPAT. Through the modeling of the Purpose, Concept, and Architecture sections, the TePPAT can be used to describe the *idea with* and the *idea in* the technology prototypes. It is concluded that use of the TePPAT can be correlated with improvements in communication, system overview, and reasoning, when working with technology prototypes.

Acknowledgements

The authors would like to thank the project members from the collaborating companies and universities. A special thanks is given to Project Manager Jens Juul Yde for the many discussions and support.

Declaration of conflicting interests

The authors declare that there is no conflict of interest.

Funding

This work was financially supported by Innovation Fund Denmark.

References

Alabastro MS, Beckmann G, Gifford G, et al. (1995) The use of visual modeling in designing a manufacturing process for advanced composite structures. *IEEE Transactions on Engineering Management* 42(3): 233–242.

Alizon F (2007) Three dimensional design structure matrix with cross-module and cross-interface analyses. In: *Proceedings of the ASME 2007 international design engineering technical conferences & computers and information in engineering conference*, Las Vegas, NV, 4–7 September, pp. 941–948. New York: ASME.

Alvarez Cabrera AA, Foeken MJ, Woestenenk K, et al. (2011) Modeling and using product architectures in industrial mechatronic product development: experiments and observations. In: *Proceedings of the ASME 2011 international design engineering technical conferences & computers and information in engineering conference*, Washington, DC, 28–31 August, pp. 319–328. New York: ASME.

Andreasen MM, Howard TJ and Bruun HPL (2014) Domain theory, its models and concepts. In: Chakrabarti A and Blessing LTM (eds) *An Anthology of Theories and Models of Design: Philosophy, Approaches and Empirical Explorations*. London: Springer, pp.173–195.

Andreasen MM, Hansen CT and Mortensen NH (1996) The structuring of products and product programmes. In: *Proceedings of the 2nd WDK workshop on product structuring*, Delft, 3–4 June, pp. 15–43. Design Society.

Bonev M, Wörösch M, Hauksdóttir D, et al. (2013) Extending product modeling methods for integrated product development. In: *Proceedings of the international conference on engineering design, ICED*, Seoul, South Korea, 19–22 August, pp. 219–228. Design Society.

Bonnema GM, Borches PD and Houten FJAM (2010) Communication: key factor in multidisciplinary system design. In: *8th conference on systems engineering research*, Hoboken, NJ, 17–19 March. Hoboken, NJ: CSER.

Borches PD (2010) *A3 architecture overviews a tool for effective communication in product evolution*. PhD Thesis, University of Twente, Enschede.

Browning TR (2001) Applying the design structure matrix to system decomposition and integration problems: a review and new directions. *IEEE Transactions on Engineering Management* 48(3): 292–306.

Bruun HPL and Mortensen NH (2012) Visual product architecture modelling for structuring data in a PLM system. IFIP AICT—advances in information and communication technology. *Montréal* 388: 598–611.

Bruun HPL, Mortensen NH and Harlou U (2014) *Interface diagram*: design tool for supporting the development of modularity in complex product systems. *Concurrent Engineering* 22(1): 62–76.

Buur J and Andreasen MM (1989) Design models in mechatronic product development. *Design Studies* 10(3): 155–162.

Checkland P and Holwell S (1998) Action research: its nature and validity. *Systemic Practice and Action Research* 11(1): 9–21.

Chesbrough HW and Teece DJ (1996) Organizing for innovation: when is virtual virtuous?*Harvard Business Review*, January, pp. 65–73.

Eppinger SD and Browning TR (2012) *Design Structure Matrix Methods and Applications*. Cambridge, MA: The MIT Press.

Erixon G (1998) *Modular function deployment—A method for product modularisation*. PhD Thesis, The Royal Institute of Technology, Stockholm.

Gebhardt N, Beckmann G and Krause D (2014) Visual representation for developing modular product families–literature review and use in practice. In: *DS 77: Proceedings of the DESIGN 2014 13th international design conference*, Dubrovnik, Croatia, 19–22 May, pp. 183–192. Dubrovnik: Design Society.

Gudlaugsson TV, Ravn PM, Mortensen NH, et al. (2014) Front-end conceptual platform modeling. *Concurrent Engineering* 22(4): 267–276.

Hansen CB (2013) Cooperating or conflicting values? A study of public and private values in public–private partnerships. In: *11th public management research conference*, Madison, WI, 20–22 June.

Hansen CT and Andreasen MM (2002) The content and nature of a design concept. In: *Proceedings of NordDesign 2002* (eds Boelskifte P and Sigurjonsson JB), Trondheim, 14–16 August, pp. 101–110. Trondheim: Department of Machine Design and Materials Technology & Department of Product Design Engineering, NTNU.

Hansen CT and Andreasen MM (2002) The content and nature of a design concept. In: *Proceedings of NordDesign 2002* (ed. Boelskifte P and Sigurjonsson JB), Trondheim, 14–16 August, pp. 101–110. Department of Machine Design and Materials Technology & Department of Product Design Engineering, NTNU, Trondheim.

Hansen CT and Andreasen MM (2003) A proposal for an enhanced design concept understanding. In: Folkeson A, Gralén K, Norell M, et al. (eds) *Proceedings of 14th International Conference on Engineering Design*. Stockholm: ICED, pp. 1–10.

Harlou U (2006) *Developing product families based on architectures: Contribution to a theory of product families*. PhD Thesis, Department of Mechanical Engineering, Technical University of Denmark, Kongens Lyngby.

Henderson RM and Clark KB (1990) Architectural innovation: the reconfiguration of existing product technologies and the failure of established firms. *Administrative Science Quarterly* 35(1): 9–30.

Herriott RE and Firestone WA (1983) Multisite qualitative policy research: optimizing description and generalizability. *Educational Researcher* 12(2): 14–19.

Houde S and Hill C (1997) What do prototypes prototype? In: Helander M, Landauer TK and Prabhu P (eds) *Handbook of Human-Computer Interaction*. 2nd ed.Amsterdam: Elsevier BV, pp. 367–381.

Hubka V and Eder WE (1988) *Theory of Technical Systems: A Total Concept Theory for Engineering Design*. Berlin; New York: Springer-Verlag.

Iansiti M (1995) Technology development and integration: an empirical study of the interaction between applied science and product development. *IEEE Transactions on Engineering Management* 42(3): 259–269.

IEEE (2011) ISO/IEC/IEEE 42010:2011 Systems and software engineering—architecture description.

Kiil H-E and Benslimane M (2009) Scalable industrial manufacturing of DEAP. In: *Proceedings of SPIE–the international society for optical engineering* (eds Bar-Cohen Y and Wallmersperger T), San Diego, CA, 8 March, vol. 7287, pp. 72870R1–72871R10. Bellingham, WA: SPIE.

Kvist M (2010) *Product family assessment*. PhD Thesis, DTU Management, Kongens Lyngby.

Mankins JC (2009) Technology readiness assessments: a retrospective. *Acta Astronautica* 65(9–10): 1216–1223.

Mortensen NH and Andreasen MM (1996) Designing in an interplay with a product modelexplained by design units. In: *Tools and methods for concurrent engineering*, Budapest, Hungary, 29–31 May.

Nilsson P and Erixon G (1998) The chart of modular function deployment. In: *Proceedings of the 4th WDK workshop on product structuring*, Delft, 22–23 October, pp. 147–154. Design Society.

Nobelius D. (2002) *Managing R&D processes—Focusing on technology development, product development, and their interplay*. PhD Thesis, Chalmers University of Technology, Gothenburg.

Otto KN and Wood KL (1998) Product evolution: a reverse engineering and redesign methodology. *Research in Engineering Design* 10(4): 226–243.

Pahl G, Beitz W, Feldhusen J, et al. (2007) *Engineering Design: A Systematic Approach* (ed. Wallace K and Blessing L). 3rd ed.London: Springer-Verlag.

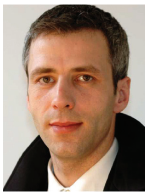
Smith D (2010) *Exploring Innovation*. 2nd ed.London: McGraw-Hill.

Steward DV (1981) The design structure system: a method for managing the design of complex systems. *IEEE Transactions on Engineering Management* 28(3): 71–74.

Stone RB, Wood KL and Crawford RH (1998) A heuristic method to identify modules from a functional description of a product. In: *Proceedings of ASME DETC DTM 98*, Atlanta, GA, 13–16 September, pp. 1–11. New York: ASME.
Tanner D, Fitzgerald JA and Phillips BR (1989) The Kevlar story—an advanced materials case study. *Angewandte Chemie International Edition in English* 28(5): 649–654.
Tjalve E (2003) *Systematic Design of Industrial Products*. Kongens Lyngby: Institute for Product Development.
Ullman DG (2009) *The Mechanical Design Process*. 4th ed.New York: McGraw-Hill.
Ulrich K (1995) The role of product architecture in the manufacturing firm. *Research Policy* 24(3): 419–440.
Ulrich KT and Eppinger SD (2008) *Product Design and Development*. 4th ed.New York: McGraw-Hill.
Yin RK (2009) *Case Study Research: Design and Methods*. 4th ed.Thousand Oaks, CA: SAGE.

Author biographies

Poul Martin Ravn is a PhD student at the Section of Engineering Design and Product Development in the Mechanical Engineering Department at the Technical University of Denmark (DTU). He holds an MSc in Design and Innovation from DTU. His current research is focused on product architectures and multi-product integration in conjunction with technology development.



Tómas Vignir Gudlaugsson is a PhD student at the section of Engineering Design and Product Development in the Mechanical Engineering Department at DTU. He has an MSc in Design and Innovation from DTU. His research is focused on the development of Platforms in conjunction with technology development.

Niels Henrik Mortensen holds a PhD and an MSc in Mechanical Engineering and is employed as a Professor at the Technical University of Denmark. He is head of the section of Engineering Design and Product Development at DTU Mechanical Engineering at the Technical University of Denmark. His main research focus is procedures and methods supporting development of Product Families based on Architectures and Platforms. Currently, there are nine researchers within the field of architecture-based product development.

APPENDIX C

Paper C

Platform based design of EAP transducers in Danfoss PolyPower A/S
Rahimullah Sarban and Tómas V. Guðlaugsson

In Proc. SPIE 8687, Electroactive Polymer Actuators and Devices (EAPAD) 2013, 86870L-1–11. San Diego, California, USA: International Society for Optics and Photonics.

Platform based design of EAP transducers in Danfoss PolyPower A/S

Rahimullah Sarban*[a], Tómas V. Guðlaugsson[b]
[a]Danfoss PolyPower A/S, Nordborgvej 80, 6430 Nordborg, Denmark;
[b]Dept. of Mechanical Engineering, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark

ABSTRACT

Electroactive Polymer (EAP) has gained increasing focus, in research communities, in last two decades. Research within the field of EAP has, so far, been mainly focused on material improvements, characterization, modeling and developing demonstrators.

As the EAP technology matures, the need for a new area of research namely product development emerges. Product development can be based on an isolated design and production for a single product or platform design where a product family is developed. In platform design the families of products exploits commonality of platform modules while satisfying a variety of different market segments. Platform based approach has the primary benefit of being cost efficient and short lead time to market when new products emerges.

Products development based on EAP technology is challenging both technologically as well as from production and processing point of view. Both the technological and processing challenges need to be addressed before a successful implementation of EAP technology into products. Based on this need Danfoss PolyPower A/S has, in 2011, launched a EAP platform project in collaboration with three Danish universities and three commercial organizations. The aim of the project is to develop platform based designs and product family for the EAP components to be used in variety of applications. This paper presents the structure of the platform project as a whole and specifically the platform based designs of EAP transducers. The underlying technologies, essential for EAP transducers, are also presented. Conceptual design and solution for the concepts are presented as well.

Keywords: EAP, transducer, platform, product architecture, product family, product organs

1. INTRODUCTION

Electroactive polymer (EAP) is a relatively new class of smart material technology which has gained increasing interest in both academic and commercial organizations over the last decades [1]. The research activities have mainly been focused on:

- Analyzing, improvement and characterization of chemical and physical properties of EAP material [2 – 8],
- Development and characterization of the necessary compliant electrodes [9 – 11],
- Construction, characterization and modeling of proof of concept transducers [12 – 21],

All the above research activities have been of particular importance for developing the fundamentals for EAP technology. However, as the EAP technology matures the need for its commercialization requires a different set of research activities. The technology can be commercialized only if its diffusion into the product world is successfully achieved. This requires development of EAP transducers specifically designed to be used in products rather than simply demonstrating a proof of concept function.

Product oriented transducer development can be carried out with two distinctive approaches:

- Transducer design and development for a single specific product, i.e. “isolated” design,
- Transducer design and development for a group of products, i.e. platform based design.

The “isolated” design approach has the advantages of being optimized to the specific product and thus performs more effective. However, such approach limits its scalability within the product as well as its reusability in other products. This lack of scalability and reusability consumes more development resources and increases products’ time to market whenever new requirements and products are considered. The platform based design approach uses commonality of products needs such that a single transducer design can be reused in different products with smallest amount of modifications. For example; Black & Decker redesigned their consumer power tools based on a platform of standard components with scalable building blocks. This reduced the development and production cost by up to 50% [22] enabling Black & Decker to be cost competitive. GE Fanuc automation which produces industrial automation system

Electroactive Polymer Actuators and Devices (EAPAD) 2013, edited by Yoseph Bar-Cohen,
Proc. of SPIE Vol. 8687, 86870L · © 2013 SPIE · CCC code: 0277-786X/13/$18 · doi: 10.1117/12.2009652

adopted the platform approach by standardizing the technology building blocks and their interfaces. This approach reduced their average development time from 20 to 6 – 9 months [23].
As EAP transducer technology can potentially be used in many and different products, EAP transducer developers can potentially use the platform approach and reduces development cost with short time to market. Danfoss PolyPower A/S, with the aim of being an EAP transducer and component supplier, has established a technology platform development project. The aim of the project is create an EAP transducer technology platform where few transducer variants are designed to be used in large number of products and applications.
This paper presents the overall structure of the project as well as the progresses being made, so far, toward creating an EAP transducer platform. Section 2 describes the overall goals of the project. Section 3 shows the structure of the project with the various work packages and resources. Section 4 contains theories being applied for platform based product development. Section 5 presents the development of a product family master plan (PFMP) for the EAP transducers platform. The paper ends with a conclusion in section 6.

Due to the scope limitation all the technical justifications and details, mathematical simulations, and experimental data are excluded from this paper.

2. PLATFORMS GOALS

A platform is a set of common components, modules or parts from which a stream of derivative products can be efficiently created and launched [22]. The goal of the EAP platform development project is; i) to offer varieties to the market based on its requirements, and ii) to introduce commonalities to the production (see Figure 1). The organs in the platform structure refer to the required physical parts and processes for design and construction of EAP transducers.

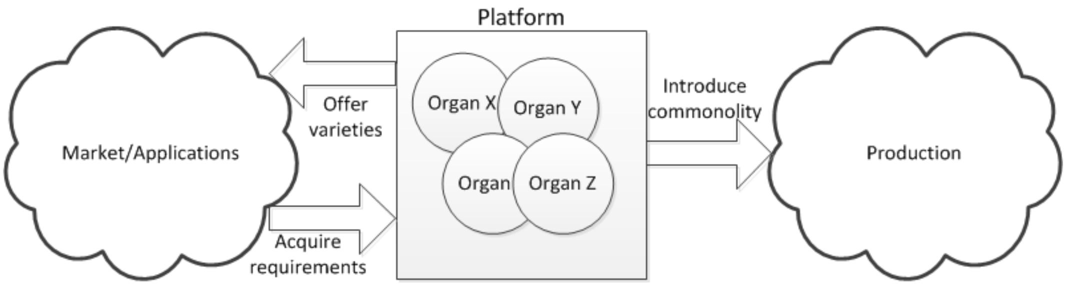


Figure 1. Graphical representation of the goals of EAP transducer platform project.

3. PROJECT ORGANIZATION AND STRUCTURE

The EAP transducer platform project was initiated in June 2011 with expected completion in May 2015. The project is collaboration between:

- Danfoss PolyPower A/S (DPP)
- Danfoss Heating Solutions (DHS)
- Bang & Olufsen (BO)
- WAVESTAR (WS)
- Technical University of Denmark (DTU)
  - Department of Chemical Engineering (DTU-C)
  - Department of Mechanical Engineering (DTU-M)
  - Department of Electrical Engineering (DTU-E)
- University of Southern Denmark (SDU)
- Aalborg University (AAU)

The project is partly financed by Denmark’s Advance Technology Foundation (ATF) and partly by the above collaborators. The project involves more than 90 individuals as full and part time contributors including 13 Ph.D. scholars. The project consists of 9 work packages (WPs) each with its distinctive task (see Figure 2). WP1- 5 are involved in development of the platform while WP6 – 9 are four lead applications for demonstration of the platform solutions.

WP1 performs material research with the aim of increasing dielectric permittivity and electrical break down strength of the material while preserving a low elastic modulus and viscous damping. The 4 aforementioned parameters constitute performance of EAP material and the corresponding transducers.
WP2 develops and optimizes production processes for automated roll to roll manufacturing of EAP film.
WP4 is researching in design and development of drive electronic solutions for the EAP transducers. The drive electronic development considers compatibility with both actuation and energy harvesting features of EAP transducers.
WP5 develops mathematical models with the aim of creating an engineering tool used to design and simulate EAP transducers systems, i.e. transducers and drive electronics in both actuation and energy harvesting applications.
WP3 design, develops, and demonstrates the platform based EAP transducer. In essence, WP3 is main developer of the platform where transducer solutions are developed and the various sub-solutions from WP1, 2, 4, and 5 are integrated.
Four different lead applications (WP6 – 9) are included in the project to demonstrate the solution of platform EAP transducers. WP6 demonstrates an actuator system where the strain of the actuator is ideally infinite. Such strain is achieved by using the inchworm movement principle in which the actuator can displace a payload substantially longer than its geometrical dimensions.
WP7 demonstrates wave energy harvesting systems based on EAP transducers. The aim of WP7 is to exploit the high power density of EAP technology and demonstrate system of up to 1 kW electrical power output. Such demonstration system can subsequently be scaled up to larger power output.
WP8 demonstrates platform EAP transducers in fluid control application e.g. controlling the flow of hot water into radiators. The aim of WP8 is to exploit the minimal energy consumption of EAP transducers when controlled to a constant position. Such minimal energy consumption is a consequence of the capacitive nature of the EAP technology as opposed to the magnetic based transducers e.g. voice coils.
WP9 demonstrates EAP transducers used in loudspeaker systems. The aim here is to exploit the fast response time and large bandwidth of EAP transducers in such high frequency application. The goal is to be able to develop flat, light, and efficient loudspeaker systems based on EAP transducers.
The aforementioned 4 lead applications have different sets of requirements which should be satisfied by the platform EAP transducers. E.g. radiator fluid control systems operate in low frequency region (below 0.2 Hz) but desired to be very efficient (operating more than 2 years with 2 units of 3V batteries). Loudspeaker system, on the other hand, operates at several kHz frequency range, desired to be flat whilst the efficiency could be of secondary priority. Moreover the incremental actuators, due to their large strain capabilities, are desired to exhibit smaller dimensions while the energy harvesting systems require large EAP transducers to harvest more energy. Hence a successful demonstration of the platforms EAP transducers in these 4 and very different applications will indicate transducers potential use in many other products.

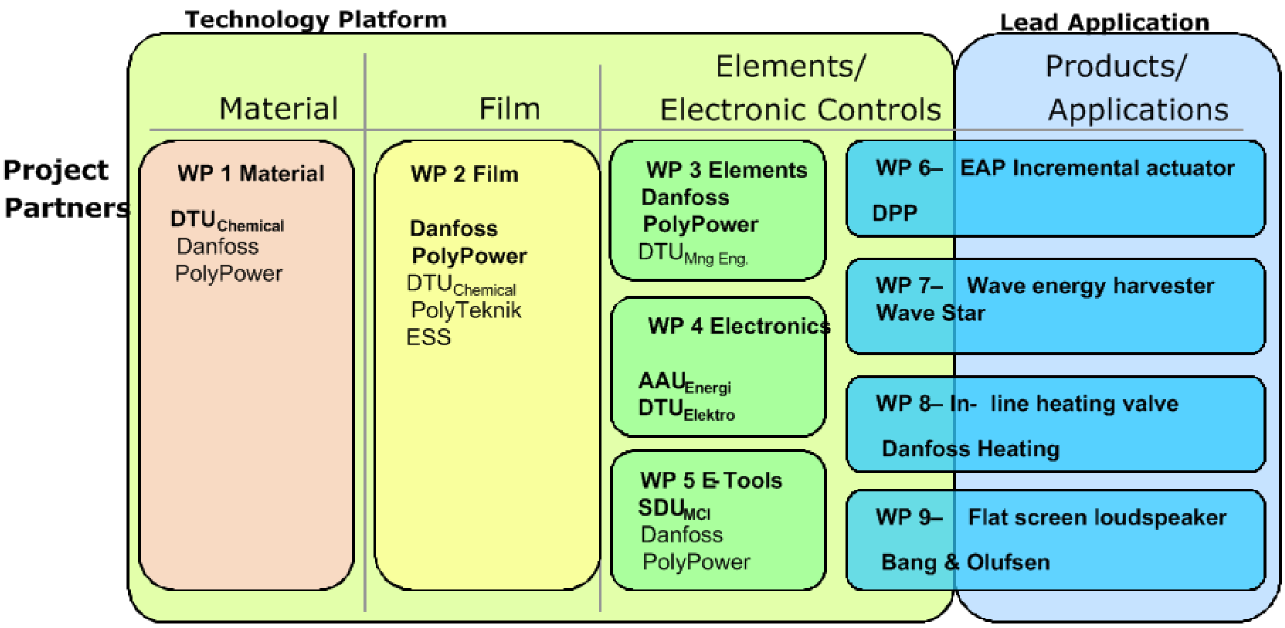


Figure 2. Structure of the platform project with various work packages and the collaborators of each work package.

4. PLATFORM DEVELOPMENT THEORY

4.1 Product architecture

Product architecture is the main part of a platform and is defined as [24]:

- Arrangement of functional elements of the products,
- Mapping of the functional elements to physical modules,
- Specifying the interface between the physical modules.

Architectures can be *modular* or *integral*. In fully modular architecture each functional element has a one-to-one map to a physical module. In integral architecture, on the other hand, a functional element can be mapped to several physical modules. The modular architecture enables the alteration or scaling of a functional element without affecting the others by replacing its corresponding physical module. Such scaling of functionality is however not possible in integral approach where either a single functional elements involves more physical modules or vice versa.

The aim, for developing EAP transducer platform here, is to create a *modular* architecture.

A Family Product Master Plan (PFMP) is a tool where the application requirements, transducers architecture, physical modules, and the interface between the physical modules can be visualized.

4.2 Product Family Master Plan (PFMP)

A product family is a larger set of end products constructed from a much smaller set of components [25]. A product family master plan (PFMP) is tool for visualizing the structure of the product family. Three distinctive but interconnected viewpoints are needed to describe a product family [26]:

- Customer view: This view should describe product family from a customer point of view [27], and identify the features which are of primary interest to customers.
- Engineering view: This view should describe the product family from a functional viewpoint, i.e. how product architecture and its varieties are realized from smaller varieties in organs of the products.
- Part view: This view should describe the physical units of the organs and their variation in material and dimensions.

Figure 3 illustrates a *principle model of a product family* [27]. Here the product family (engineering view) is oriented such that it should show variety to the market (customer view) and commonality to production (part view).

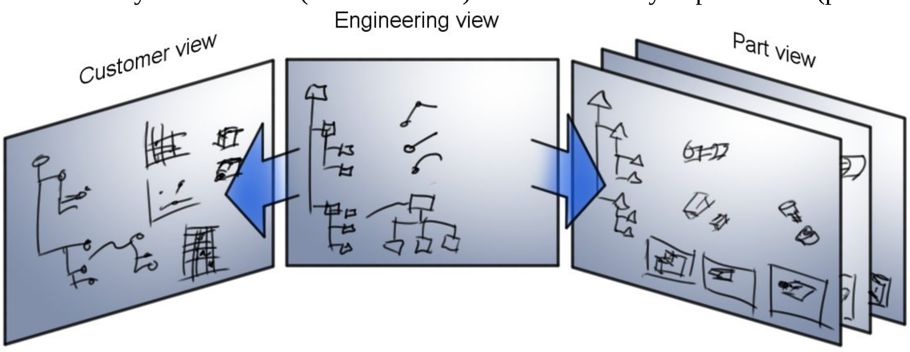


Figure 3. Principle model of a product family. Reproduced from [27].

Each of the three views, in Figure 3, needs to be modeled individually and subsequently the interrelations between them has to be established. As the detail modeling and interrelations of the three views are out of scope of this paper, only the results for the three views are included and discussed here.

4.3 Interrelation between customer, engineering and part views

Figure 4 shows the three views, schematically, illustrating on how the customers features are realized (left to right) as well as how a new variant of a physical module can add value to a specific feature (right to left).

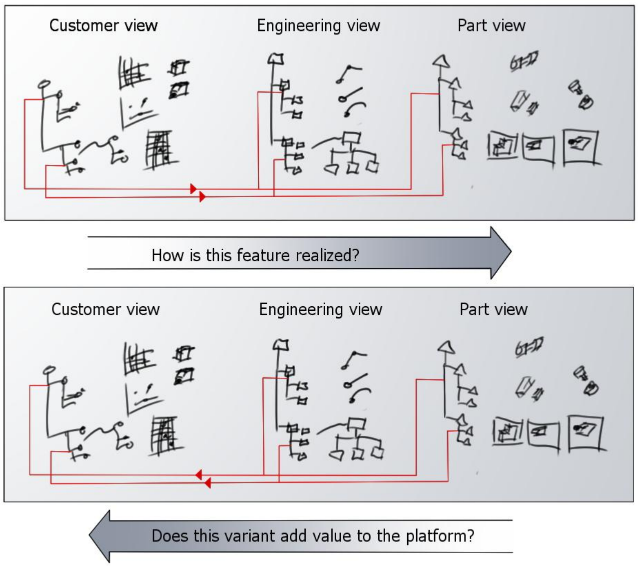


Figure 4. The three views of a PFMP and their interconnections. Reproduced from [27].

The hierarchal structure of the three views illustrates that requirements are initiated from customers (applications) and should be translated to the engineered solutions which accommodate such requirements. Creating such engineered solutions then requires parts of certain dimensions and characteristics. In essence the *requirement flow*, in a PFMP, has a top-down hierarchy. Conversely, introducing a new variant in part view of PFMP can enable a more optimized engineered solution and as such more value to a specific feature can be added. Therefore the *value flow*, in a PFMP, has a bottom-up hierarchy.

5. EAP TRANSDUCER PLATFORM

In order to create product family platform for EAP transducers, the three necessary views described in preceding sections have to be created and interrelated. The creation of the three views is based on the research carried out by Danfoss PolyPower A/S combined with the customer and production experience gathered over the last decade. Due to the scope limitation, the details on creating the views are not included here. Instead the results of the three views and their interrelations are presented.

5.1 Customer view

Figure 5 shows an extract of customer view with three distinguished classes:

- Transducers features: Features of a transducer defines its operation mode in an application. These features are classified in three main operation modes, i.e. actuation, energy harvesting, and sensing. Each of the operation modes has its own specific sub-features e.g. whether a transducer in actuation mode is used for positioning, vibration or surface pressure generation.
- Transducers primary output: This part of the customer view indicates the main output of interest in an application. Some output parameters e.g. force and stroke of a transducer are usually interrelated; however some applications may define one single output parameter as being the primary output of interest.
- Technical requirements: This part of the customer view shows the generic requirements which can apply to all transducers regardless of their operation modes and area of applications.

In order to be able to relate the customer view of Figure 5 to engineering view, the requirements of customer views are quantified. Figure 6 shows an extract of some of the quantified requirements. Note that, due to scope limitation of this paper, only the most essential features and requirements are shown in Figure 6. Furthermore, a single feature may have different meaning depending on the type of application, e.g. force in actuator application may refers to the generated force by actuator while in energy harvesting application it may refer to external forces exciting a EAP generator. This application based interpretation of features will affect the mapping of features to EAP transducers organs and have to be addressed in the engineering view. Figure 6 shows that the quantified features have large scope. A single engineered design is difficult, if not impossible, to fulfill the entire range and therefore the engineering view has to provide varieties of EAP transducers designs for specified sets of requirements.

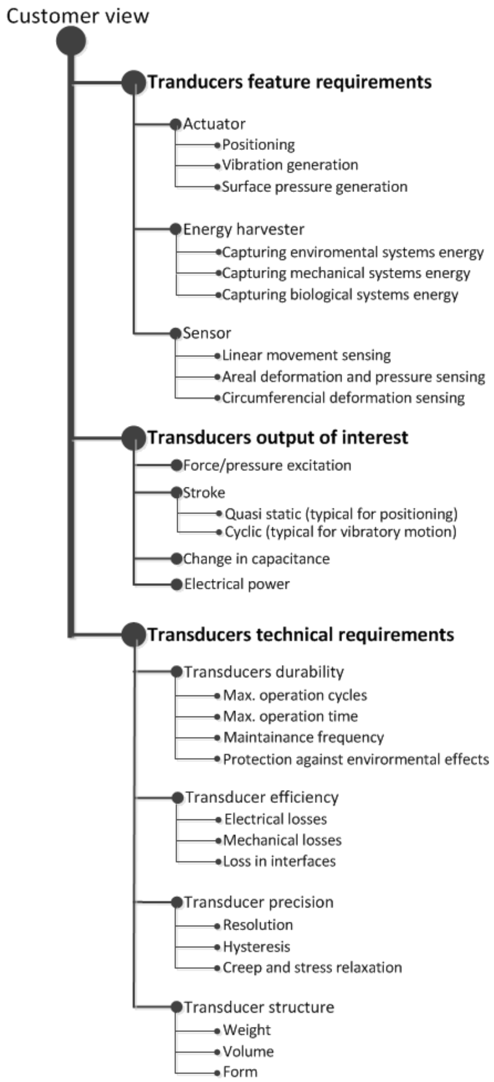


Figure 5. Features diagram of the customer view of EAP transducers product family.

Typical ranges		Actuator application			Energy harvesting application		Sensor application		
		Positioning	Vibration	Surface pressure	Waves energy capture	Other energy sources	Linear sensors	Areal sensors	Circumferencial sensors
Force	<10 N		X					X	
	<100 N	X		X			X		X
	<1000 N					X			
	>1000 N				X				
Stroke	<1 mm		X						
	<10 mm			X					
	<100 mm	X				X	X	X	X
	>100 mm				X				
Frequency	<1 Hz				X	X		X	
	<10 Hz			X			X		X
	<100 Hz	X							
	>100 Hz		X						
Cycles	in kilo							X	
	in mega	X		X	X	X	X		X
	in giga		X						
Resistance	<10 Ohms		X		X	X			
	<100 Ohms	X							
	<1000 Ohms			X			X	X	X

Figure 6. Quantified features of the customer view of EAP transducers product family.

5.2 Engineering view

Engineering view is the core of a product architecture enabling to create a product family. The engineering view has to offer varieties to the market (customer view) while introducing commonalities to production (part view). This can be achieved, respectively, by reusing transducers organs while preserving easy scalability in size and variability in features.

Figure 7 shows engineering view of the transducer PFMP based on the physical and processing organs. Four generic physical organs namely EAP film, mechanical suspenders, electrical interconnectors, and encapsulations are included as they apply to all three types of operation modes (actuation, sensing and energy harvesting). Each of the four generic physical organs exhibit variants with distinct characteristics. It is eventually the assembly of one variant from each of the four organs which constitute the behavior, function and properties of a transducer.

The processing organs in Figure 7 contain structuring, gluing and segmenting of EAP film. Structuring process provides a certain shape to the EAP film. Gluing process glues layers of a multilayer rolled or stacked structure resulting in a monolithic structure. Segmentation process increases the durability of transducers and is achieved by introducing segments within transducer or within a system of transducers.

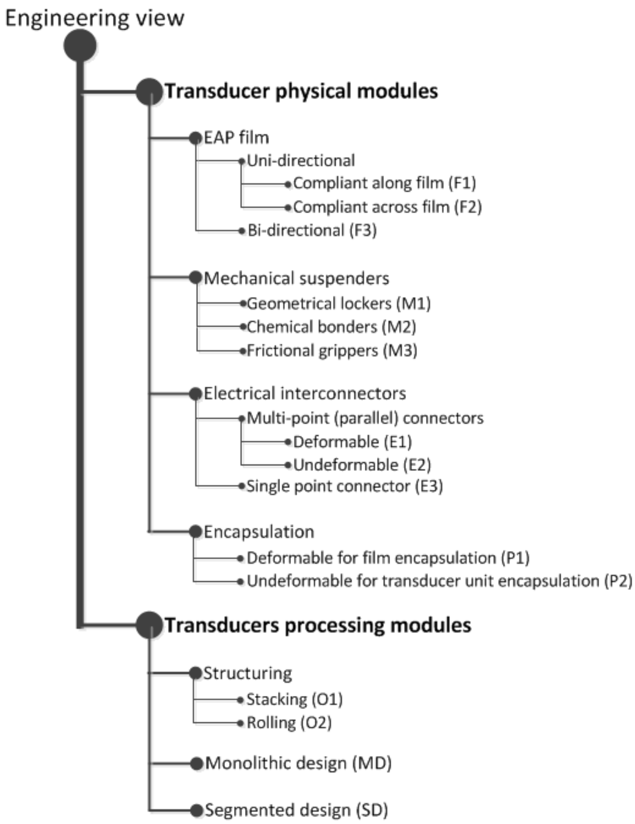


Figure 7. Engineering view of EAP transducer product family.

5.3 Part view

Part view describes the physical structure of product family and contains the physical assemblies and parts [27]. Parts are the physical unites with specified material and dimensions. Figure 8 shows an extract of the part view where only parts related to EAP film are illustrated. Here the EAP film organ of engineering view is available in various materials and dimensions.

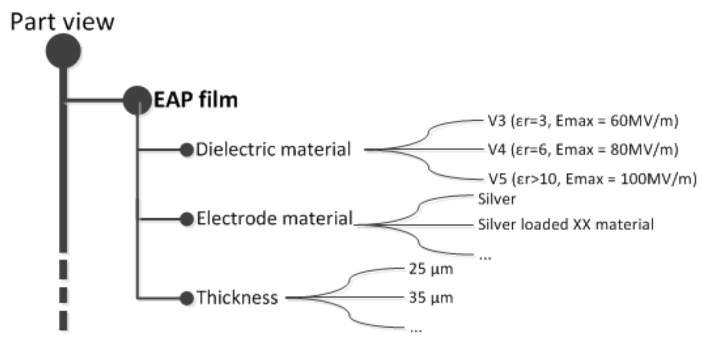


Figure 8. An Extract of part view of EAP transducer product family.

5.4 Platforms EAP transducers

The aim of EAP transducer platform is to provide varieties to the market and commonality to production. In order to facilitate that six EAP transducers are designed as platform transducers:

1. Axial 1: Organ code (F2, M2R, E2, P2, O2, MD),
2. Axial 2: Organ code (F2, M2R/M3, E2/E3, P1, O2, MD),
3. Linear: Organ code (F1, M1, E1, P1, O2, MD, SD),
4. Radial: Organ code (F1, M2F, E1, P1, O2, MD),
5. Areal: Organ code (F1/F3, M2F, E2/E3, P1, O1, MD),
6. Incremental: Organ code to be determined.

The organ code of each transducer indicates its organs (Figure 7) being used for its construction. E.g. Axial 1 uses an EAP film with corrugation across the sheet (F2), rigid chemical bonders for mechanical suspension (M2R), multipoint low deformation electrical interconnectors (E2), rigid housing for encapsulation (P2), rolling process (O2) and the layers are glued together to form a monolithic structure (MD). Note that some transducers, e.g. Axial 2 and Areal, are alternating organs which increase their features flexibility for application requirements. E.g. Areal transducer uses E2 electrical interconnector, when used for actuation while it can use E2 or E3 if used for sensing.

Figure 9 shows a diagram of the platform transducers with their typical characteristics range. Since a one-fit-all transducer solution is difficult, if not impossible, each transducer of Figure 9 can satisfy a certain set of requirements.

Axial 1

This transducer is designed to satisfy most of the conventional actuation features e.g. positioning of objects, vibratory excitation, and providing pushing force. This transducer operates with both compressive and tensile loadings. Force transfer between Axial 1 transducer and the surrounding system is thorough its mechanical suspension.

Axial 2

This transducer is similar to Axial 1 from construction point of view. However Axial 2 transducer exhibit very different features e.g. creating a direct and constant pressure excitation over a non-uniform surface. Axial 2 can also be used for linear positioning in the perpendicular direction (2^{nd} axes) to its primary rolled axes, or proving a linear sensing feature. The force transfer between Axial 2 transducer and the surrounding system is through transducers main body while mechanical suspensions are used for positioning the transducer.

Linear

This transducer is designed primarily to provide large strokes and forces in low to moderate frequency ranges. These characteristics fit well with wave energy harvesting applications as well as large stroke with low frequency linear positioning applications. The Linear transducer operates with tensile loadings and the force transfer between the transducer and the surrounding system is through the mechanical suspenders.

Radial

This transducer is designed to provide radial pressure or measure circumferential changes in structures. These types of actuation and sensing features enables novel solutions such as pressure generation on human body and breathe monitoring, to mention a few. The force transfer between the transducer and the surrounding system is thorough transducers body while the mechanical suspensions are used for transducer positioning.

Areal

This transducer is designed to provided or measure areal deformations. In actuation mode, it provides a large area movement with high frequency while in sensing mode it can detect areal pressure being applied. Such characteristics of

Areal transducer, in actuation mode, can be used e.g. for haptic feedback, flat loudspeaker and similar. The force transfer between the transducer and the surrounding system is through its main body which mechanical suspenders are used to position the transducer.

Incremental

Incremental transducer is designed to provide largest possible strokes (ideally infinite). This transducer concept is based on an inchworm movement where the sequences of gripping, extending, and releasing of the different sub-sections of the transducer increment its position. This type of transducer is designed to satisfy the need for large strokes with smallest amount of space and minimum weight.

Note that the graphical illustration of Figure 9 does not represent all the geometrical variants of platform transducers. E.g. Axial 1 transducer can be configures cylindrical, as illustrated in Figure 9, or oval, triangle, square or any other required shape. This shows that varieties of Axial 1 transducer are offered to the market while preserving reuse of both physical and processing organs.

	Potential application	Loading possibilities	Typical force range	Typical stroke range	Typical freq. range	Cycle range	Overall serial resistance
Axial 1	Linear positioner	Compressive and tensile	Medium	Medium	Medium	Mega cycles	<5 Ohms
	Vibration generator			Low	High	Giga cycles	
Axial 2	Surface pressure gen.	Tensile	Medium	N/A	Low	Mega cycles	<100 Ohms
	Linear positioner		Medium	Medium	Medium		<5 Ohms
	Linear sensor		N/A	High	Low		<100 Ohms
Linear	Linear positioning	Tensile	High	High	Low	Mega cycles	<5 Ohms
	Energy harvesting				Low		
Radial	Radial pressure gen.	Compressive and tensile	Medium	N/A	Low	Mega cycles	<5 Ohms
	Circumferencial sensor	Tensile	N/A	High	Medium		<100 Ohms
Areal	Surface vibration gen.	Compressive	Low	Low	High	Giga cycles	<5 Ohms
	Areal sensor	Tensile	N/A	N/A	Low	Mega cycles	<100 Ohms
	Pressure sensor	Compressive	N/A	N/A	Low	Mega cycles	<100 Ohms
Incremental	Large stroke & compact positioner	Compressive and tensile	Medium	High (ideally infinite)	Low	Mega cycles	<5 Ohms

Figure 9. Platforms EAP transducers with their typical characteristic ranges.

5.5 EAP Transducer pre-PFMP

By mapping transducer solutions of the engineering view (Figure 9) to requirement of the customer view (Figure 6) an interrelation between the two views can be visualized (see Figure 10). E.g. applications with large stroke and force requirements can be satisfied with a Linear transducer while high frequency application are offered Areal and Axial 1 transducers.

Typical ranges		Actuator application			Energy harvesting application		Sensor application		
		Positioning	Vibration	Surface pressure	Waves energy capture	Other energy sources	Linear sensors	Areal sensors	Circumferencial sensors
Force	<10 N								
	<100 N								
	<1000 N								
	>1000 N								
Stroke	<1 mm								
	<10 mm								
	<100 mm					X	X	X	X
	>100 mm				X				
Frequency	<1 Hz				X	X		X	
	<10 Hz						X		X
	<100 Hz								
	>100 Hz								
Cycles	in kilo							X	
	in mega	X		X	X	X	X		X
	in giga		X						
Resistance	<10 Ohms		X		X	X			
	<100 Ohms	X							
	<1000 Ohms			X			X	X	X

Figure 10. Visualization of the interrelation between the customer requirements from customer view and transducer solutions from engineering view.

The mapping and visualization of needs, solutions, and organs are the main part for a PFMP which help easy decision makings on how features are realized or how value is added to the features (Figure 4). As a part of EAP transducer platform project a pre-PFMP has been developed. Figure 11 shows an extract of graphical illustration of the pre-PFMP. The applications requirements (customer view) are listed on the left of the pre-PFMP followed by transducer concepts and its organs (engineering view) on the right. In order to avoid visualization complexity the part view is not included in Figure 11.
Although development of the pre-PFMP of Figure 11 is still an ongoing activity, it has so far been a useful tool for internal and external communication. The pre-PFMP has been used to identify the main requirements and features from application point of view and how they can be realized by transducer solutions. Furthermore the pre-PFMP has been helpful to provide arguments for eliminating some organs which did not add value to the applications requirements and as such reduced the varieties to production.

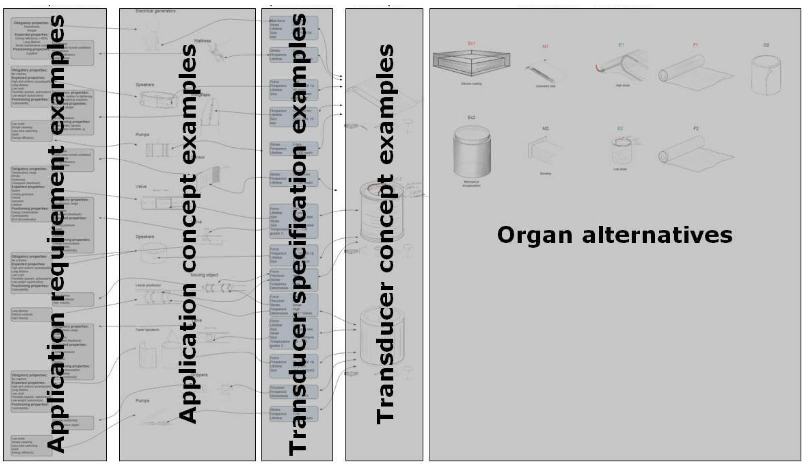


Figure 11. A graphical illustration of EAP transducer pre-PFMP.

6. CONCLUSION

Extensive research, at various commercial and scientific organizations over the last 2 decades, has developed the EAP technology to the point of its commercialization. Commercialization of EAP technology can only be achieved if it is successfully diffused into products. Thus the need for a new research area namely EAP based product development is emerging.
Choosing a certain product development method is a strategic decision which has to be made by the leadership of each organization. Danfoss PolyPower A/S aims at being the EAP transducer supplier and therefore focuses on platform based transducer development which can satisfy largest possible numbers of applications. The tool which is used for modeling the platform of EAP transducer, PFMP, has provided important decision making arguments.
The platform based EAP transducer development has introduced varieties to applications with high level of organ reuse, i.e. commonality to production. This approach can potentially reduce the unit cost and increase repeatable manufacturing of EAP transducers.

REFERENCES

[1] Bar-Cohen, Y., Electroactive Polymer (EAP) Actuators as Artificial Muscles: Reality, Potential, and Challenges, SPIE PRESS, 2nd Edition (2004).
[2] Brochu, P., Pei, Q., Advances in Dielectric Elastomers For Actuators and Artificial Muscles, Macromolecular Rapid Communications 31(1), 10-36 (2010).
[3] Zhang, X. Q., Wissler, M., Jaehne, B., Broennimann, R., Kovacs, G., Effects of crosslinking, prestrain and dielectric fillers on electromechanical response of a new silicone and comparison with acrylic elastomer, Proc. SPIE 5385, (2004).
[4] Kofod, G., Dielectric elastomer actuators, PhD Thesis, The Technical University of Denmark, (2001).

[5] Kofod, G., Risse, S., Stoyanov, H., McCarthy, D. N., Sokolov, S., Kraehnert, R., Broad-spectrum enhacement of polymer composite dielectric constant at ultralow volume fractions of silica-supported copper nanoparticles, ACN Nano 5(3), 1623-1629 (2011).
[6] Kofod, G., Styoanov, H., Kollasche, M., Risse, S., Ragusch, H., Rychkov, D., Dansachmuller, M., McCarthy, D. N., Nano-scale materials science for soft dielectric: Composites for dielectric elastomer actuators, IEEE International Conference on Solid Dielectric, 987-1-4244-7945-0, (2010).
[7] Kussmaul, B., Risse, S., Wegener, M., Kofod, G., Krüger, H., Matrix stiffness dependent electro-mechanical response of dipole grafted silicones, Smart Materials and Structures 21(6), 064005 (2012).
[8] Bejenariu, A. G., Boll, M., Lotz, M. R., Vraa, C., Skov, A. L., New elastomeric silicone based networks applicable as electroactive systems, Proc. SPIE 7976, 79762V (2011).
[9] Carpi, F., Chiarelli, P., Mazzoldi, A., Rossi, D. D., Electromechanical characterization of dielectric elastomer planar actuators: comparative evaluation of different electrode materials and different counterloads, Sensor and Actuators A 107, 85-90 (2003).
[10] Rosset, S., Niklaus, M., Dubois, P., Shea, H. R., Mechanical characterization of a dielectric elastomer microacturator with ion-implemented electrodes, Sensors and Actuators 144, 185-193 (2008).
[11] Pimpin, A., Suzuki, Y., Kasagi, N., Microelectrostrictive actuator with large out-of-plan deformation for flow control application, Microelectromechanical systems 16(3), 753-764 (2007).
[12] Carpi, F., Rossi, D. D., Dielectric elastomer cylindrical actuators: electromechanical modelling and experimental evaluation, Material Science and Engineering C. Biomimetic and Supramolecular Systems C24(4), 555-562 (2004).
[13] Kaal, W., Herold, S., Electroactive Polymer Actuators in Dynamic Applications, IEEE TMECH 16(1), (2011).
[14] Lochmatter, P., Kovacs, G., Wissler, M., Characterization of dielectric elastomer actuators based on a visco-hyperelastic film model, Smart Material and Structures 16, 477-486 (2007).
[15] Pelrine, R. E., Kornbluh, R. D., Joseph, J. P., Electrostriction of polymer dielectric with compliant electrodes as a means of actuation, Sensors and Actuators A 64, 77-85 (1998).
[16] Son, S., Goulbourne, N. C., Dynamic response of tubular dielectric elastomer transducers, International Journal of Solids and Structures 47(20), 2672-2679 (2010).
[17] Wang, P., Lassen, B., Jones, R. W., Multi-scale mechanical modeling of a tubular actuator with compliant metal electrodes, Proc. SPIE 7642, (2010).
[18] Wissler, M., Mazza, E., Modeling and simulation of dielectric elastomer actuators, Smart Material and Structures 14, 1396-1402 (2005).
[19] Lotz, P., Matysek, M., Flittner, K., Schlaak, H. F., Modeling of non ideal dielectric elastomer stack actuators, Proc. SPIE 7642, 764214 (2010).
[20] Pei, Q., Pelrine, R., Stanford, S., Kornbluh, R., Rosenthal, M., Electroelastomer rolls and their application for biomimetic walking robots, International Conference on Science and Technology of Synthetic Metals 0379-6779, 129-131 (2003).
[21] Sarban, R., Lassen, B., Willatzen, M., Dynamic Electromechanical Modeling of Dielectric Elastomer Acuators With Metallic Electrodes, IEEE TMECH 17(5), 960-967 (2012).
[22] Meyer, M. H., Lehnerd, A. P., The power of product platforms, New York: The Free Press, (1997)
[23] Sanchez, R., Collins, R. P., Competing - and Learning - in Modular Markets, Long Range Planning 34(6), 645-667 (2001).
[24] Ulrich, K. T., The role of product architecture in the manufacturing firm, Research Policy 24, 419-440 (1995).
[25] Ulrich, K. T., Tung, K., Fundamental of Product Modularity, Massachusetts Institute of Technology, ASME, Atlanta, US, (1991).
[26] Andersen, M. M., Hansen, C. T., Mortensen, N. H., The Structuring of Product and Product Program, Proc. of the WDK Workshop on Product Structuring, The Netherlands, Delft University of Technology, (1996).
[27] Harlou, U., Mortensen, N. H., Developing product families based on architectures: Contribution to a theory of product families., DTU - Technical University of Denmark, Kgs. Lyngby, (2006).

APPENDIX D

Paper D

EAP high-level product architecture
Tómas Vignir Guðlaugsson, Niels Henrik Mortensen, and Rahimullah Sarban

In Proc. SPIE 8687, Electroactive Polymer Actuators and Devices (EAPAD) 2013, 868710-1–8. San Diego, California, USA: International Society for Optics and Photonics.

EAP high-level product architecture

T. V. Gudlaugsson[*a], N. H. Mortensen[a], R. Sarban[b]
[a]Dept. of Mechanical Engineering, Technical Univ of Denmark, Produktionstorvet 426, 2800 Kgs. Lyngby, Denmark; [b]Danfoss PolyPower A/S, DK-6430 Nordborg, Denmark

ABSTRACT

EAP technology has the potential to be used in a wide range of applications. This poses the challenge to the EAP component manufacturers to develop components for a wide variety of products. Danfoss Polypower A/S is developing an EAP technology platform, which can form the basis for a variety of EAP technology products while keeping complexity under control. High level product architecture has been developed for the mechanical part of EAP transducers, as the foundation for platform development.

A generic description of an EAP transducer forms the core of the high level product architecture. This description breaks down the EAP transducer into organs that perform the functions that may be present in an EAP transducer. A physical instance of an EAP transducer contains a combination of the organs needed to fulfill the task of actuator, sensor, and generation. Alternative principles for each organ allow the function of the EAP transducers to be changed, by basing the EAP transducers on a different combination of organ alternatives.

A model providing an overview of the high level product architecture has been developed to support daily development and cooperation across development teams.

The platform approach has resulted in the first version of an EAP technology platform, on which multiple EAP products can be based. The contents of the platform have been the result of multi-disciplinary development work at Danfoss PolyPower, as well as collaboration with potential customers and research institutions. Initial results from applying the platform on demonstrator design for potential applications are promising. The scope of the article does not include technical details.

Keywords: EAP technology, multi-product development, technology platform, platform development, product architecture, multi-product modeling, platform, transducer.

1. INTRODUCTION

There is an increasing demand to reduce the time to market for new products. This has pushed many corporations into adopting product platforms to be able to push a wide variety of products onto the market in less time than before. Many product manufacturers have developed product platforms to be able to deliver a wide variety of products, with a high degree of reuse of parts and manufacturing equipment, at a competitive price. Black & Decker redesigned their consumer power tools products in the 1970’s, based on a common platform of standard components and scalable building blocks. The new platform lowered production costs and simplified derivative product development, and allowed Black & Decker to reduce prices considerably – in some cases more than 50% [1]. A key element in Black & Decker’s platform strategy was their ability to develop derivative products at an accelerated rate. A reduction in development time for products based on commonality has also been shown at Bang & Olufsen where reuse of a DVD standard design lead to an estimated reduction in research and development (R&D) time of 40 man-months, and a 15% reduction of R&D resources for the development of audio products based on standard designs [2]. These benefits are not limited to producers of consumer products. GE Fanuc automation, a producer of industrial automation systems, managed to reduce the average development time for new product architectures from twenty months to six to nine months, by adopting a platform approach that included the definition of technology building blocks and standardized interfaces [3].

EAP technology is currently in a state of ongoing research and development projects, but no large scale commercialization of EAP technology based products has yet taken place. There are several strategies for transducer productions, such as mass production of few product variants, platform based production of a wide variety of product

[*] tomg@mek.dtu.dk; +45 45256253; mek.dtu.dk

Electroactive Polymer Actuators and Devices (EAPAD) 2013, edited by Yoseph Bar-Cohen,
Proc. of SPIE Vol. 8687, 868710 · © 2013 SPIE · CCC code: 0277-786X/13/$18 · doi: 10.1117/12.2009714

variants with reuse of designs and components, and tailored production of a vast variety of custom designed products. A wide range of potential applications has been identified, and more may be identified in the future. Therefore, it is necessary for an EAP component manufacturer to be prepared to deliver to a wide range of customers and customer requirements.

In an effort to produce a wide variety of cars while keeping down development and production costs, the Volkswagen group has employed a platform approach across brands such as Audi, Volkswagen, Skoda, and Seat. Models based on the A-platform have shared 50% of the components across the brands, where 50% has been model specific components. Recently, to further increase the individuality of each model, and increase the reuse of components, an even more modular approach has been decided upon and now the goal is to reach a stage where 20% of each model is platform based, 60% based on cross platform modules, and only 20% unique to each model [4].

Danfoss PolyPower aims at commercializing EAP transducers for a wide variety of applications. A platform approach enables Danfoss PolyPower to develop transducers for a wide variety of applications, based commonalities that allow for effective use of R&D resources and production equipment. One step along this way is the development of an EAP high-level product architecture, with the aim of being prepared to deliver a wide variety of EAP technology based transducers. The goal of adopting a platform approach is to limit the needed R&D resources for each new application that may come along, by identifying potential standard design elements at a high level, which can be scaled and combined to suit the particular application.

Within this publication, the term product refers to a transducer and the term application refers to a product or system that employs, or can employ, an EAP transducer as a component.

This contribution looks into what product architecture is, how it relates to technology platforms and product platforms, and presents a high-level product architecture developed at Danfoss PolyPower.

2. PRODUCT ARCHITECTURE

The product architecture is at the heart of platform based development. Ulrich defines product architecture as “(1) the arrangement of functional elements; (2) the mapping from functional elements to physical components; (3) the specifications of the interfaces among interacting physical components” [5]. Depending on the design of the product architecture, it may be more or less suited to a platform based development. In a one-to-one mapping of functional elements to physical componenta, where each physical component provides only one function, the performance of each physical component can be altered with less effect on the other functions, than if a single physical component performs many functions. In a fully modular architecture, functionality of the product can be changed by exchanging one physical component with another without affecting the functionalities of the other components. As a contrast to this, a fully integral architecture maps functions and physical components in a complex relationship where functions are mapped to multiple physical components and physical components map to multiple functions. In an integral architecture, changes to the functionality or a physical component cause disruptions in both other functionalities and physical components, and so any changes to the product design are more complex than in modular architectures.

2.1 Product Family Master Plan

There are various definitions in literature for what a product platform is. While some definitions specify components, others are based on broader terms, such as elements, technology, and parameters [6]. A common ground in the definitions is the sharing of contents of the platform across multiple products. In this publication, the definition of a platform is as follows:

“A platform is a structural description of a product assortment, product family or a product. A platform is an instance of an architecture that only includes existing standard designs and their interfaces, i.e. interfaces among the standard design, interfaces among standard designs and design unit and/or interfaces among standard designs and the surroundings.” [2]

Harlou also differentiates between three levels of both architectures and platforms; Assortment, product family, and product. At the product level, one individual product is covered. At the product family level, multiple products are covered, that share standard designs. The assortment level covers multiple product families, addressing standard designs, design units, and interfaces, across the product families.

Harlou presented the Product Family Master Plan (PFMP) as a model of a product platform [2]. At its core are three distinct, but interconnected views that are shown in Figure 1: customer view, engineering view, and part view. These views are mirrored in what Harlou calls a principle model of a product family, shown in Figure 2 [2].

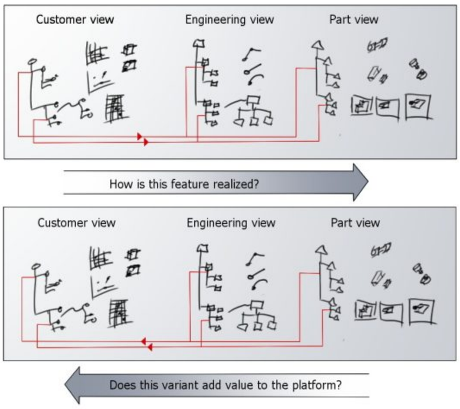


Figure 1:The three views of the PFMP provide different perspectives on the product platform, aimed at providing either more detail on how a feature is realized, or how a particular variant adds value to the customer. Reproduced from Harlou [2].

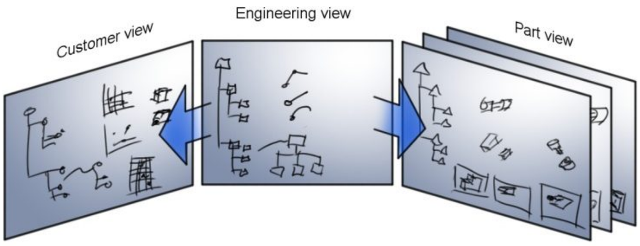


Figure 2: This principle model of a product family shows the perspectives of the three views of the PFMP. Note that as there are multiple part views, each corresponding to a single product variant. Reproduced from Harlou [2].

Harlou uses generic organ diagrams, as seen in Figure 3, to describe the architecture of the product platform. In the generic organ diagram, optional functions can be represented, as can optional interfaces that do not exist in all product variants. Various modularisation options can be indicated on an organ diagram by encapsulating organs in dotted lines. The modularisation is based on engineering judgement, founded on information on market needs and the production processes involved.

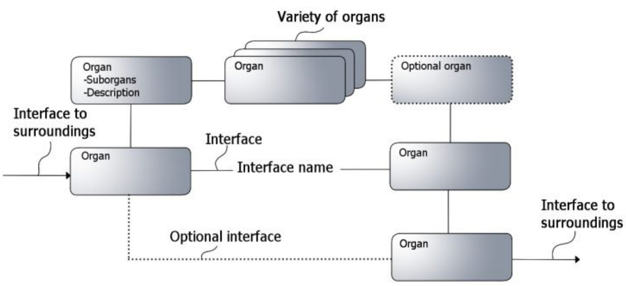


Figure 3: This symbolic generic organ diagram shows the organs that are part of a platform, along with their interfaces. Reproduced from Harlou [2].

Figure 4 shows an example of organ encapsulation from Pedersen [7], where encapsulation is a more general term than modularization. Encapsulation encompasses not only part modularization, but also the encapsulation of organs, which is achieved not in assembly, but in fabrication. Utilizing organ encapsulation may be in the form of delaying production processes that create product variants, allowing a unified production process up to a point and moving the order decoupling point closer to final assembly.

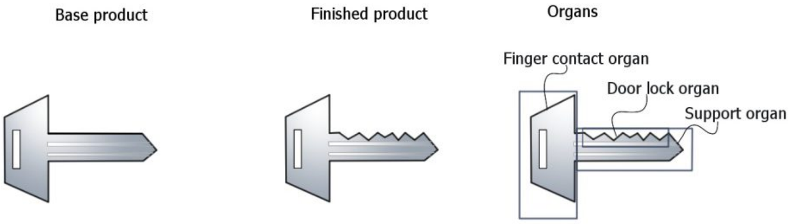


Figure 4:An example of organ encapsulation, a more general form of modularisation, on an organ level. In this example a generic part can be mass produced, while specific instances are achieved in low volume production processes. Reproduced from Pedersen [7].

2.2 The product concept platform

The product concept platform, in the case of Danfoss PolyPower, exists as a link between technology development and platform based product development. Its function is to support the development of product platforms on the basis of technology development.

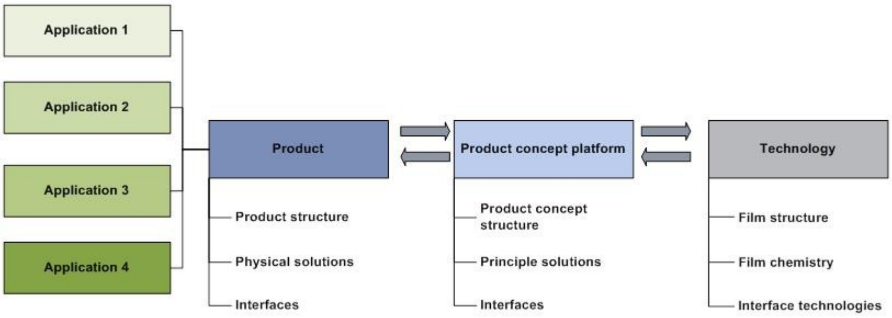


Figure 5: The product concept platform serves as a link between product development and technology development.

The concept platform acts as a link between the needs of potential applications, and the technology development that aims to provide the foundation for fulfilling those needs. The detailed design of parts and components lies outside the product concept platform, but it supports the design through the organization of technological and principal solutions for design. The product concept platform can be seen as a standardization of technology use with the product portfolio, in an effort to reduce the flexibility needed in production processes and increase the value of technology knowhow in the company.

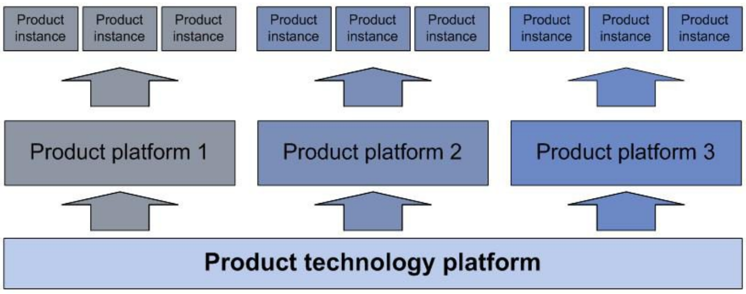


Figure 6: Product platforms that cater to diverse market demands can share the same product concept platform.

Product platforms can build upon the product concept platform to provide a broad product base for related applications. By developing separate product platforms on the basis of the product concept platform, diverse application requirements can be fulfilled on the basis of the same technologies and principles. Each product platform can then be aimed at certain shared characterizing customer requirements. In the product platforms, designs and parts can be standardized, and in some cases shared between product platforms, without stretching standard designs too far. However, the product concept platform can ensure that the solution space for the product platforms stays within the areas of technological expertise of the company. If new technological solutions appear to be needed for a particular application, this need can be compared to the content of the product concept platform, which enables an evaluation of whether the new technological solution provides benefits that can be reaped in other product platforms as well.

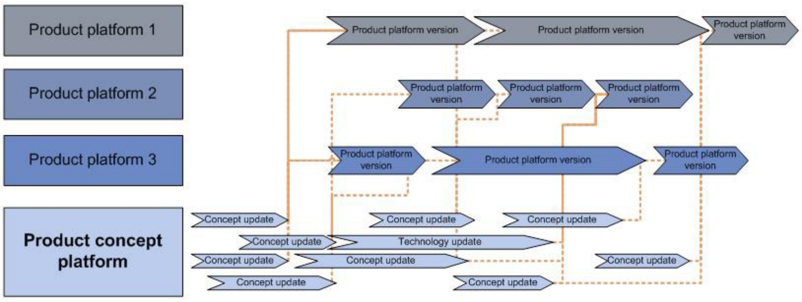


Figure 7: Technology development, and concept updates, can be fed from the product concept platform to product platforms based on it. Similarly, product platforms provide feedback for the needed capabilities of the product concept platform.

3. EAP HIGH-LEVEL PRODUCT ARCHITECTURE

Danfoss PolyPower's EAP high-level product architecture was developed as a part of an ongoing technology platform development project. It is a predecessor to a fully fledged product concept platform. The core of the EAP high-level product architecture is a generic description of an EAP transducer, which includes all necessary mechanical functionalities. In the generic description each function is represented by an organ, which is defined by the function it provides. A generic organ diagram provides an overview over the organs and how they relate to each other. In the case of the EAP high-level architecture, a graphical representation that followed a typical configuration of an EAP transducer was found to be beneficial as a communication tool. Figure 8 shows the graphical representation of the organ breakdown of an EAP transducer. For the team involved in the development, this representation provided a link from the abstract thinking of the organ diagram and the development tasks in the project. The dotted lines indicate that a particular organ may not be present in all possible configurations of an EAP transducer.

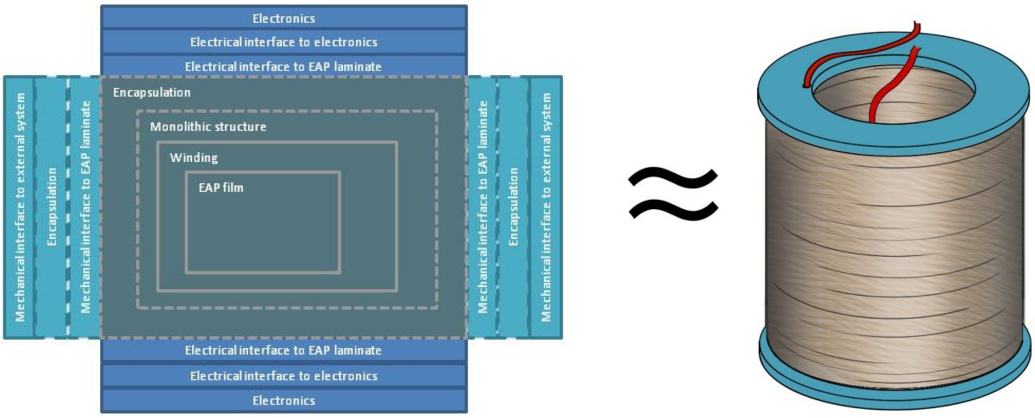


Figure 8: The generic breakdown of an EAP transducer in a graphical form (left) that shows the typical configuration of the organs, which also highlights the potential interfaces between the organs. The organs represent functionalities present in typical EAP transducers as in the case of an Axial 1 type transducer (right).

For each organ, multiple alternatives have been developed, and therefore figure 8 does not show any single physical representation of an EAP transducer. An EAP transducer represents a physical instance of a particular combination of organ alternatives, with particular dimensions and in a particular configuration. Figure 9 shows the Pre-PFMP, a document developed in the project as a tool to identify and communicate the organs in a typical transducer. The organs, and the alternative organs, are the building blocks of an EAP transducer, as seen from the perspective of the project team.

The organs in the center of the illustration indicate a form of organ encapsulation. In production, these are not assembly modules but represent different choices of fabrication steps in the production line. Once the EAP film has been wound, the type of film cannot be changed without unwinding it. Similarly, once a particular monolithic structure has been achieved, neither winding nor EAP film can be changed. Any step in the production process that comes after the particular step, winding for example, can however be varied depending on the product variant that is to be produced. Thus, several different products, which vary in type of monolithic structure, encapsulation, and EAP laminate structure, can be achieved based on the same choices of EAP film and winding.

3.1 Pre-PFMP

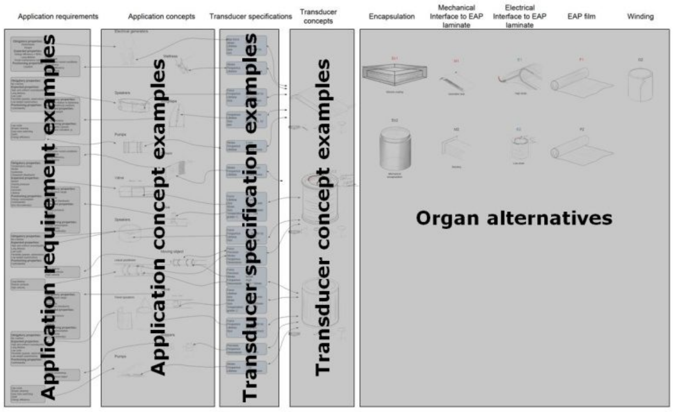


Figure 9 The Pre-PFMP is a graphic representation of example applications, example components, and organ alternatives.

The Pre-PFMP contains five distinct areas: (1) A collection of *application requirements examples*. These represent estimated requirements for some of the applications that have been considered as possible EAP suitable applications in the project. (2) *Application concept examples* show how Danfoss PolyPower's EAP technology could potentially be applied in the exemplified applications. These are presented as early stage ideas, and provide inspiration for the development of the EAP technology by depicting EAP technology as a subcomponent in a customer's product. (3) *Transducer specification* examples are a shortlist of specifications for each application concept shows the needed performance for the transducer concept to fulfill the particular application requirements. (4) *Transducer concept examples* show concepts for EAP technology based components that could provide the customer with the needed functionality are illustrated. The illustrations are accompanied with a listing of the particular organ alternatives that are used in the particular component concept.

The organ alternatives area includes six columns: Encapsulation, mechanical connection, electrical connection, element structure, winding, and folio. Each of these columns corresponds to an organ in figure 8, listing the alternative technological solutions that are being developed to provide the functionality of the organ in an EAP transducer.

The breakdown of the transducer into organ alternatives includes a rationale for each of the alternatives. An organ alternative must have a rationale for its inclusion in the Pre-PFMP, as the contents of the Pre-PFMP are also representative of development tasks requiring R&D resources. This rationale emphasizes what distinguishes the particular organ alternative from other alternatives within the same organ type. Within Electrical interface to EAP laminate, organ alternatives were characterized by estimates of their relative electrical conductivity and their ability to withstand strain parallel to the electrical interface.

The organ alternative is further described in a document that functions as a design manual for design engineers. This document summarizes the knowledge acquired in the project on the particular organ alternative. The document contains information on the rationale behind the organ alternative, the principles behind it, and a description of the design factors that have been identified. The design engineer can gain a more detailed insight from the design manual on how the organ alternative performs, how to dimension the organ alternative, what parts of the design are fixed and what parts are determined for each variant, and what pitfalls have been identified. Much of the engineering is therefore performed in the platform development, which reduces the engineering effort required to design a new variant of the organ combination.

The Pre-PFMP served as both a communication tool for parties outside the development team, and within the team itself. Changes would be noted directly onto a printout on A0 size paper, and the document would then be updated with the results from the meetings. The Pre-PFMP document provides an overview of the applications considered within the project, as well as examples of other possible applications, what kind of EAP transducers might be used in the applications, and a breakdown of the transducer into building blocks.

The Pre-PFMP can be seen as a way of communicating how market demands can be fulfilled by transducer concepts based on the platform. In figure 10, *how can we achieve it* indicates this left-to-right reading order of the Pre-PFMP. It also illustrates how the transducer concepts can be constructed, by comparing relative performance ratings of organ alternatives and the requirements of the particular market. This, in turn provides information to the platform developers about the requirements that need to be fulfilled by the platform. Conversely, reading the Pre-PFMP from right-to-left gives an answer to *what do we want to achieve* (see figure 10). It is possible to contemplate different combinations of organ alternatives, see how these come together into transducer concepts, and how they can be put to use in customer's application.

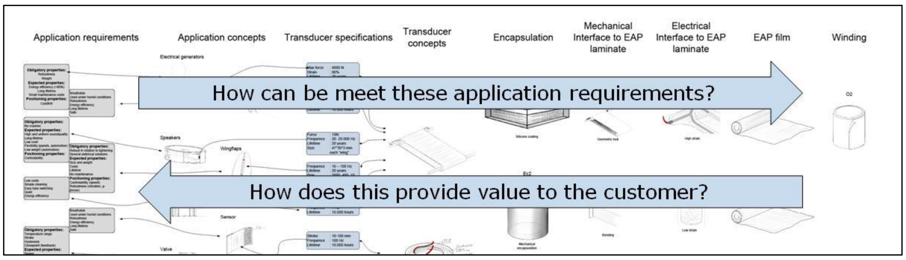


Figure 10: A close-up of the Pre-PFMP. The Pre-PFMP, when read from left to right, shows how application requirements and concepts lead to component concepts that require certain design elements provided by organ alternatives.

3.2 Prototype production based on the platform

The solutions developed within the project have been applied in various prototype designs. The prototypes vary in size, form, and intended application. Similarly, they must fulfill different requirements and enter heterogeneous use environments. The applications are heating control valves, loudspeakers, energy generators, anti-speckle systems, and infusion pumps. At this point, two types of transducers based on the platform have been produced for use as prototypes; Axial 1 and Linear. These two types are both based on the same winding process, but do not share other organ alternatives.

3.2.1 Axial 1 type prototypes

From a mechanical point of view, four of the prototypes share the exact same organ alternatives from the Pre-PFMP. Thus, they comprise the same functions, but they vary in the physical form. They share the same construction principles, in the form of an Axial 1 type component (see figure 8, right), but differ in length, width, wall thickness, and configuration in the application. No further technology development was needed to produce the additional variants, as the knowledge of how to achieve such a component was contained in the EAP high-level product architecture. The unique engineering effort to develop each prototype was limited to dimensioning the transducer and designing the mechanical interfaces unique to the particular application.

3.2.2 Linear type prototypes

Three prototypes have been produced using an organ combination that has been named Linear (see figure 11). As with the Axial 1 component, the EAP prototypes varied in dimensions and performance specifications, but were based on the same organ alternatives and principles for mechanical construction. Therefore, the knowhow on how to construct the transducer could be reused, and built upon for subsequent prototypes.

Figure 11: Linear type transducers have been produced for use in prototypes for three different applications, requiring different dimensions, and thus performance, for each one.

3.2.3 Commonality

In the project, two transducer types have been produced. To produce them, eight organ alternatives have been developed. Of those, two are common between the types. A combined number of seven variants have been produced for the two types, which could reuse the already developed organ alternatives. From a commonality perspective, after the first Axial 1 transducer was produced, the organ alternatives could be reused in three more variants. Similarly, after the design of the first Linear transducer, the organ alternatives could be reused in two more variants.

When the organ alternatives for Axial 1 had been developed, three variants could be designed without further development. Furthermore, with the additional development of three more organ alternatives, a new transducer type could be produced in three variants.

4. CONCLUSION

There are numerous examples from various industries where platform strategies have been successfully implemented, with benefits such as cost reductions, reduced time to market for derivative products, and lower R&D resource use for new products. The adoption of a platform approach in the case of Danfoss PolyPower has shown that a high-level transducer architecture can be applied to a variety of applications. Results from applying the platform in prototype development indicates that a single combination of organ alternatives from a high-level transducer architecture can be the basis for transducers with varying dimensions and performance specifications. Furthermore, with the additional development of three more organ alternatives, a new transducer type could be produced in three variants.

ACKNOWLEDGMENTS

The authors would like to thank the Danish National Advanced Technology Foundation for its financial support.

REFERENCES

[1] Meyer, M. H. and Lehnerd, A. P., [The power of product platforms], New York: The Free Press, (1997).
[2] Harlou, U., "Developing product families based on architectures: Contribution to a theory of product families.," DTU - Technical University of Denmark, Kgs. Lyngby, (2006).
[3] Sanchez, R. and Collins, R. P., "Competing - and Learning - in Modular Markets," *Long Range Planning*, vol. 34, no. 6, pp. 645-667, (2001).
[4] Pötsch, H. D., "Our roadmap to profitable growth," Volkswagen AG, Frankfurt, 2008.
[5] Ulrich, K., "The role of product architecture in the manufacturing firm," *Research Policy*, vol. 24, pp. 419-440, (1995).
[6] Hölttä-Otto, K., "Modular Product Platform Design," Helsinki University of Technology, (2005).
[7] Pedersen, R., "Product Platform Modelling - Contributions to the discipline of visual product platform modelling," DTU Management Engineering, Kgs. Lyngby, (2010).

APPENDIX E

Paper E

Front-End Conceptual Platform Modeling
Tómas Vignir Guðlaugsson, Poul Martin Ravn, Niels Henrik Mortensen, and Rahimullah Sarban

Published in Concurrent Engineering: Research and Applications (2014), 22(4): 267–76.

Original Article

Concurrent Engineering: Research and Applications
2014, Vol. 22(4) 267–276

DOI: 10.1177/1063293X14546430
cer.sagepub.com
SAGE

Front-end conceptual platform modeling

Tómas V Guðlaugsson[1], Poul M Ravn[1], Niels H Mortensen[1] and Rahimullah Sarban[2]

Abstract

Platform thinking has been the subject of investigation and deployment in many projects in both academia and industry. Most contributions involve the restructuring of product programs, and only a few support front-end development of a new platform in parallel with technology development. This contribution deals with the development of product platforms in front-end projects and introduces a modeling tool: the Conceptual Product Platform model. State of the art within platform modeling forms the base of a modeling formalism for a Conceptual Product Platform model. The modeling formalism is explored through an example and applied in a case in which the Conceptual Product Platform model has supported the front-end development of a platform for an electro-active polymer technology. The case describes the contents of the model and how its application supported the development work in the project. The conclusion is that the Conceptual Product Platform model supports stakeholders in achieving an overview of the development tasks and communicating these across multidisciplinary development teams, as well as making decisions on the contents of the platform and providing a link between technical solutions and market requirements.

Keywords

Conceptual Product Platform, product platforms, technology platforms, multi-product development, platform development, platform modeling, front-end development

Introduction

Industry faces an increasing demand for shorter product development time and better economies of scale. Previous studies have shown that considerable savings can be achieved through platform-based development. Black and Decker's redesign of the power tool product lines in the 1970s enabled them to lower production costs, reduce development time, and simplify the design of derivative products (Meyer and Lehnerd, 1997).

Reduced development time and R&D resource expenditure through platform-based design have also been shown for audio products (Harlou, 2006) and automation equipment (Sanchez and Collins, 2002). However, these cases deal with incremental innovation projects, that is, where existing product portfolios are rationalized or where new product portfolios are developed for well-known products and markets.

In radical innovation projects (Dewar and Dutton, 1986), there are often considerable uncertainties involved in the different facets of the development: market, technology, product, and production. These uncertainty factors may be even more confounded when the radical innovation project is run in a technology-push strategy. Earlier cases of technology-push efforts (Christensen, 1998) show that there are hurdles to be overcome to successfully commercialize a new technology, one of which is identifying the right markets and applications for the technology. In an ongoing technology-push effort aimed at commercializing a novel technology in a public–private partnership

[1]Section of Engineering Design and Product Development, Department of Mechanical Engineering, Technical University of Denmark, Kongens Lyngby, Denmark
[2]LEAP Techology, Kongens Lyngby, Denmark

Corresponding author:
Tómas V Guðlaugsson, Section of Engineering Design and Product Development, Department of Mechanical Engineering, Technical University of Denmark, Produktionstorvet 426, 2800 Kongens Lyngby, Denmark.
Email: tomg@mek.dtu.dk

project (Hansen, 2013), measures are implemented to counteract technology-push difficulties. One such measure is aimed at reducing the effect of market, product, and production uncertainties by following a platform-based approach to enhance the potential to meet a wide range of market needs. This requires the ability to model and describe the contents of the platform, as it is developed in the front end of a radical innovation project, in a way that is able to deal with the uncertainties in market, product, and production.

While there are numerous examples in the literature of the application of platform-based development in mature product development environments, there are not many that deal with the front end of radical innovation. Description of support tools for front-end platform development for such cases is lacking.

This contribution explores the state of the art within product architecture and product family modeling, presents a Conceptual Product Platform (CPP) model as a tool to aid front-end product platform development, and describes a case where the tool has been applied.

This article is based on the work previously reported in Proceedings of the Electroactive Polymer Actuators and Devices 2013 conference (Guðlaugsson et al., 2013), which presented preliminary results. This article enhances the coverage of existing literature and the challenges of modeling a front-end product platform and presents a more mature description of the CPP model and its modeling formalism, as well as the contents of the model in an industrial case and the experiences of using the model in the case.

State of the art

Through this state of the art, the following topics will be explored: product architectures and product architecture modeling, product family modeling, and knowledge sharing and creation to support product platform development.

Product architecture

Product architecture is an explicitly defined perspective on the structure of a product. One take on an explicit definition of a product architecture includes "(1) the arrangement of functional elements; (2) the mapping from functional elements to physical components; (3) the specifications of the interfaces among interacting physical components" (Ulrich, 1995: 420).

Commonality across product architectures, often achieved through modularization (Ulrich, 1995), is a characteristic that differentiates product family design from design of individual products and is linked to various benefits of alignment, such as economies of scale, increased product variety, reduced development time, and the enabling of parallel development tasks (Gershenson et al., 2003; Jiao and Tseng, 2000; Martin and Ishii, 2002; Prasad, 1996; Sanchez, 2004).

Product architecture modeling. Product architecture models aim to capture information on, and communicate a description of, the product architecture. They can be based on a variety of perspectives, some of which are covered below. Function models focus on the functionality provided by the products. Organs represent function carriers within products (Andreasen, 1980; Bruun and Mortensen, 2012; Ernst Eder, 2011). Function-means modeling uses a hierarchical tree to represent a breakdown of functions and design solutions (means) to those functions. Enhanced function-means models add interactions between elements in the tree to provide a more comprehensive product model (Schachinger and Johannesson, 2000). The Function–Behavior–State/Structure (FBS) model links the function, behavior, and structure of the product in order to describe *what* the product does, *how* the product does it, and *why* the product does what it does (Gero, 1990; Rosenman and Gero, 1994). Design structure matrices (DSMs) combine function modeling with matrices, depicting relations within the product. This enables the use of software algorithms to identify modules, which are especially beneficial in products with complex interactions (Eppinger and Browning, 2012; Hölttä and Salonen, 2003). Functional structure heuristics focus on flows in a function model of the product to identify modularization candidates in the product (Stone et al., 2000).

Product family modeling. The Product Family Master Plan (PFMP) models product families with an emphasis on including a multi-domain view, based on the Theory of Technical Systems and Domain Theory, which includes not only the product but also the market and production in the view of the product family (Andreasen and Mcaloone, 2008; Harlou, 2006; Hubka and Eder, 1988; Mortensen and Hvam, 2011). The PFMP model has been used in mature industries, and later developments of the PFMP mirror this as they add support to modeling production, commercial, organizational, and complexity cost issues (Kvist, 2009; Pedersen, 2010). Three-dimensional design structure matrix (DSM-3D) and DSM variety add dimensions to the DSMs to allow simultaneous analysis of multiple products. Product Family Heuristics use heuristic analysis of flows in the product family to aid modularization and support commonality, but none of these include market or production issues directly. The enhanced function-means model can provide a model of a platform with variants modeled through configurable components while relying on a hierarchical tree branching at each design solution alternative in the platform as well as comprehensive data on each design solution, constraint, function, and their interactions (Johannesson and Claesson, 2005).

Knowledge sharing and learning to support platform development

Technology, defined here broadly as the ability to achieve an effect based on a scientific principle that requires in-depth knowledge about the scientific principle to apply and produce, is a central element in the front end of platform-based development and requires knowledge-seeking activities and sharing of the acquired knowledge between stakeholders. Three forms of knowledge, (1) know-how, (2) know-why, and (3) know-what, have been defined for knowledge architectures (Sanchez, 2000). Of these, know-why, answered through the research of new technologies and principles for future generations of a product, and know-what, answered by exploring new product concepts and architectures, are central to the front end of platform development.

Technology-intensive firms have developed technology platforms to support the reuse of technology and engineering knowledge within the organization, across both business units and product families (Nasiriyar and Jolly, 2007; Shapiro, 2006). Technology platforms are potentially of great importance for technology-intensive organizations, but there is little operational support to be found in the literature on how they can be applied and articulated in early-stage development. While the use of technology wikis to support platform development has been described in the literature (Levandowski et al., 2012), they are aimed at gathering, sharing, and integration of technological knowledge across a large organization at a higher level, not as a support tool for front-end development of product platforms.

The challenges of modeling a front-end product platform

Commonality across variants within product families is of high relevance in product family development and may support economies of scale, shorter development time, and product variety. Product architecture modeling and, in particular, product family modeling provide support for sharing physical components across products in product families. Technology platforms, on the other hand, focus on the sharing of non-physical assets within organizations in support of reuse across product families. Products must, however, not be viewed in isolation—the purpose of the product is a central knowledge factor in product design.

Existing product family architecture models described above rely on rigid modeling formalisms and/or aim at optimizing design variables for modularization to support commonalities. However, existing models rely on detailed information on product design, which is difficult to fulfill in the uncertain environment at the front end of platform-based development. Technology platforms provide a support tool to share non-physical assets but lack support in how to model these non-physical assets during development and in relation to the purpose of the product.

What the literature does not cover is how to support front-end platform development within a dynamic solution space for an uncertain purpose while supporting commonality for future product families.

The CPP

The tool described in this section aims at supporting front-end platform development, to model and communicate the foundation of the product portfolio of the organization, within a dynamic environment with uncertainties on many levels.

The tool builds upon the previous work discussed in section "State of the art," especially the PFMP (Harlou, 2006). While these existing platform models focus on the product side of platforms, extending into part and process domains, the CPP aims to create an overview at a higher level of abstraction. Existing platform models provide support to model product families under the following conditions: (1) the organization has in-depth knowledge of the market, (2) existing product portfolios to base product development on, and (3) existing production processes for their product families. The CPP aims to support development in the rare case when the organization lacks (1) a clearly defined market or knowledge of the market, (2) existing products to base a platform on, and (3) matured production processes.

At this level of abstraction, the product concept structure, principal solutions, and key interfaces, in future or existing products, are modeled visually. An overview is thus obtained to communicate both the capabilities and developed solutions that exist within an organization and can be exploited to produce technology-based products. Through a CPP model, an organization should be able to describe what the market requires, in terms of technical solutions or technological capability, and what the organization is able to provide, or needs to acquire the capability of providing. While detailed part design lies outside the scope of the CPP, it allows for standardization of principal solutions and technology use within a product portfolio, increasing the probability of commonality in production processes and achieving a greater value from technological know-how within the organization.

The CPP is envisioned to be able to provide a foundation for multiple product platforms, catering for diverse application requirements. While the product platforms may not be able to provide significant sharing of common parts and components, they can be based on the same technologies, scaling principles, and/or production processes.

Modeling formalism

This section describes the modeling elements of a tool developed to model a CPP, as shown in Figure 1. These modeling elements can be used to summarize, collect, and identify information on what is required from the platform, what the platform can provide, and what the platform needs to contain to be able to compete in the market. Therefore, each of the modeling elements should be viewed as input to the neighboring modeling elements.

The *application requirements* are a list of requirements for applications, market segments, and use scenarios, which can clarify what needs to be taken into account when developing the CPP (Marion and Simpson, 2006). The requirements are statements that describe the needs and expectations of the stakeholders in the intended market that need to be fulfilled in order for the product to be accepted within the particular application (Holt et al., 2012). They may represent requirements fulfilled by competing products, or incumbents in the case of new market entry, or be based on explorative market research or collaboration with potential customers.

Application concepts illustrate particular solutions, in which product concepts fulfill application requirements. These may represent conceptual use scenarios that need to be supported or systems that the product concepts must become part of or integrated into.

The *product specifications* state the needed performance of the product in order for the product to fulfill the requirements of a particular application within the context of a particular application concept. They represent key specifications that influence the choice of organ alternatives or highlight where the CPP currently lacks capabilities.

Product concepts illustrate products that are, or may be, achievable by combining organ alternatives from the CPP. The concepts are illustrated along with the particular organ alternatives that provide the required functionality.

An *organ* provides an internal function within a product and is also known as a function carrier or functional unit (Hubka and Eder, 1988). It produces an effect and in turn provides an internal function, such as when the friction of two plates held together by a bolt provides the function of connecting the two plates (Mortensen, 1999). The organ diagram, based on the generic organ diagram (Harlou, 2006), depicts the generic architecture of the product concepts through the organization of organs within the product concepts. Some organs may not be needed in all products (or product types); they may provide added value or only be needed in some applications.

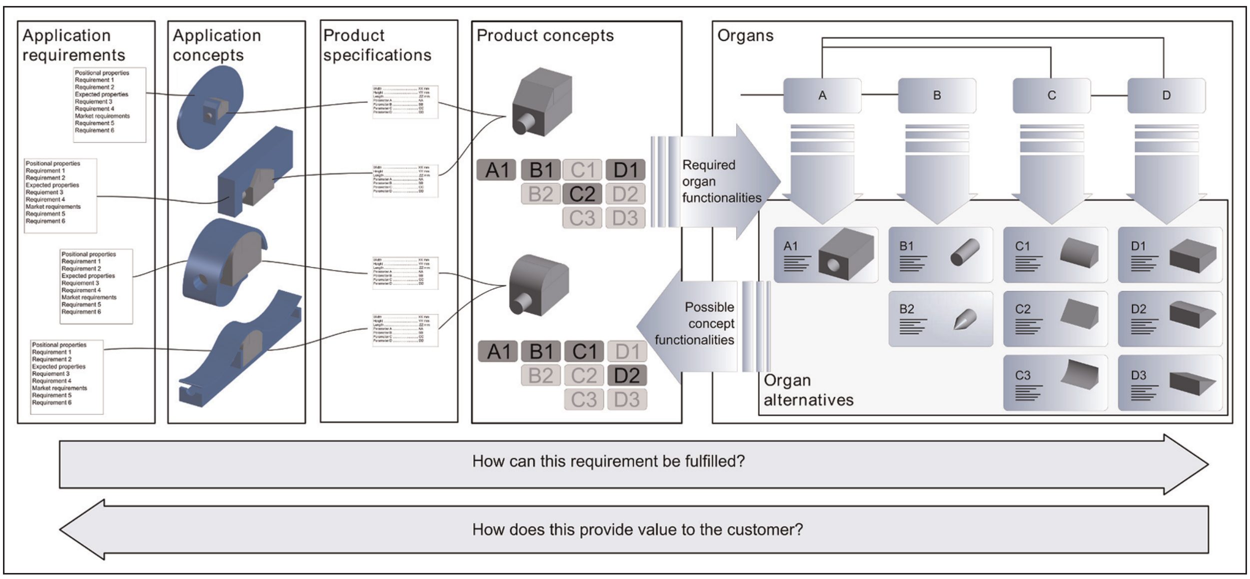


Figure 1. An overview of the modeling elements in the Conceptual Product Platform.

Organ alternatives represent alternative means of acquiring the internal function to be provided by the organ. Each alternative may perform differently on a variety of relevant parameters, which serve as rationale for the organ alternative's inclusion in the platform: performance or feature levels, trade-off curves, technology "s-curves" (Nieto et al., 1998), technology readiness levels (Mankins, 1995), or technical capabilities of the organization.

Reading the CPP model. A core element in the CPP model is the horizontal reading order, illustrated in Figure 1. When read from left to right, the CPP aims to show how an application requirement can be met through the platform contents, while a right to left reading order aims to show how platform elements can provide value to the customer. The placement of the applications to the extreme left is chosen to indicate that the contents of the CPP should arise as a consequence of application requirements. The contents of the CPP can be iteratively refined through this reading order—when the contents fulfill the application requirements and include only those organ alternatives that provide value to the applications, the CPP may be considered saturated. The visual format of the model is intended to support communication of its contents to both internal and external stakeholders.

Electro-active polymer CPP case

The tool presented in the previous section was developed in a case study, as part of a collaborative technology platform project in Denmark. The research approach is based on action research (Checkland and Holwell, 1998), with primary data collection methods being observation, field notes, interviews, and documents from the case project. The project, initiated in June 2011, aims to mature an electro-active polymer (EAP) technology through a collaborative consortium of multiple organizations from industry and academia. The project is partly funded by the Danish National Advanced Technology Foundation (DNATF). This article focuses on the application of the CPP to support the development of a platform for the mechanical construction of EAP transducers, which is intended to form the foundation of the future products of Danfoss PolyPower (DPP). DPP has 17 employees but is a fully owned subsidiary of Danfoss A/S with around 23,000 employees. The DPP EAP is a dielectric silicone film material (EAP film) with a corrugated surface on which a metal electrode is deposited. The corrugated EAP film is laminated to produce an anisotropic EAP film, which expands in a direction perpendicular to the corrugation when high voltage is applied (Tryson et al., 2009).

The CPP model from the case project

A model of the CPP was gradually filled in as the development work progressed. Figure 2 shows a late incarnation of an overview poster used in the project work, in which hand sketches illustrate the contents in the overview. The model was implemented using Microsoft® Visio®, with graphs prepared in Microsoft® Excel®. The contents of the CPP model in the EAP case are described in this section.

The application requirements comprise the main identified requirements, based on interviews with application experts within the DNATF project. Estimated application requirements for additional applications, based on explorative market research, supplement those from within the DNATF project but are considered more uncertain. For each application, the requirements are categorized based on the Kano (1995) model to highlight which parameters are most important.

The application concepts comprise sketches of EAP transducers applied to fulfill the particular application requirements. They represent early-stage ideas to provide inspiration for the development of the platform elements and what the platform may need to be prepared for. The strategy for DPP is to develop and market business-to-business (B2B) products so that the sketches depict EAP transducers as a subcomponent in a customer system.

Transducer specifications list estimated values of the primary identifiable parameters of a transducer for the particular applications. Primary actuator parameters, such as force, stroke, and frequency, are most frequent, but further specifications, such as lifetime, size, strain, and temperature ranges, are included if deemed crucial for the particular application. The precision—mirroring the access to data on application requirements—ranges from particular specifications, through quantifiable ranges, to relative descriptions such as high or low.

Product concepts are represented by sketches of transducer concepts. They illustrate the design of various EAP transducer concepts, along with the organ alternatives they comprise, linked to application requirements through the transducer specifications. The concepts in Figure 2 are the most promising concepts developed within the project and provide a basis for deciding which organ alternatives are necessary to fulfill the application requirements.

Figure 3 shows two versions of an organ diagram, showing the same organs, which are used in the project. One is based directly on the generic organ diagram (Harlou, 2006), and the other has a more direct link to the structure of the EAP transducers, illustrated by the linear actuation Axial 1 in Figure 3. In the latter, interfaces are implicitly represented by either adjacency of the boxes or the box-within-a-box representation in the

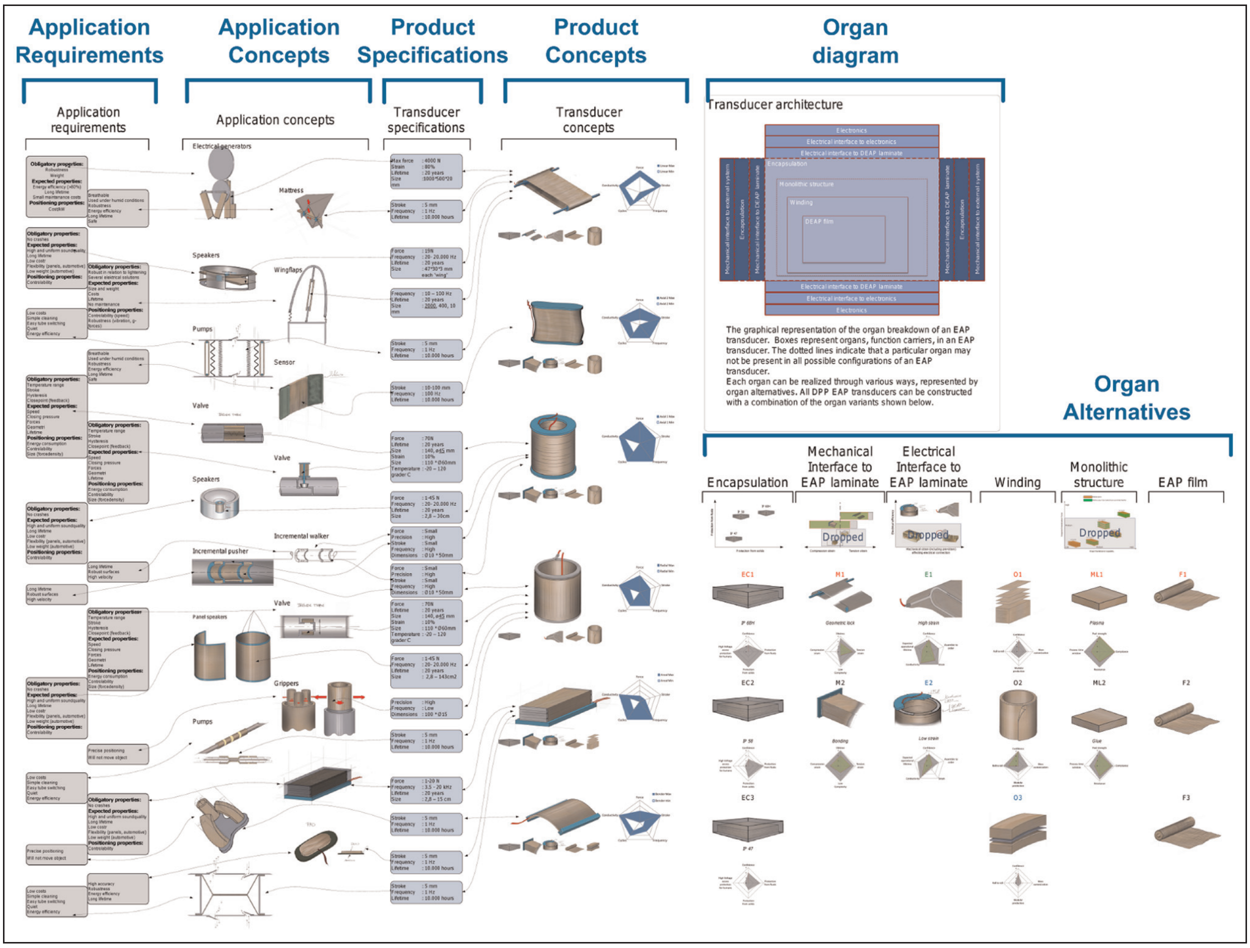


Figure 2. The CPP model from the case project shows an overview of the development tasks.
CPP: Conceptual Product Platform; DPP: Danfoss PolyPower; EAP: electro-active polymer.

central part of the figure. In this version, the hierarchy in the central part of the figure reflects the construction of the EAP transducers and can assist in ensuring coherence between process and product architectures (Sanchez, 2000). Both versions are used in parallel to ensure that interfaces are explicitly defined.

Organ alternatives are listed for six organs from the organ diagram: encapsulation, mechanical interface to EAP laminate, electrical interface to EAP laminate, winding, monolithic structure, and EAP film. The mechanical interface to external systems, electrical interface to electronics, and electronics were considered outside the scope of the work covered in this article. The organ alternatives represent technologically or conceptually different means to achieve the required functionality of the particular organ. They are derived from application requirements through transducer concepts but are decoupled from individual applications. The organ alternatives differ in their intended performance, providing a broader solution space than if a single alternative was used. This provides the rationale for inclusion within the platform and R&D resource expenditure. The performance of each organ alternative, either intended or verified performance, is illustrated graphically in the CPP. Comparison graphs for selected organs include organ alternatives that have been dropped as the feasibility of better performing organ alternatives has been verified.

Supporting documentation. In practice, further documentation of findings related to the CPP was maintained to a more detailed degree than was feasible to do on the CPP model directly. The detailed findings were therefore documented in reports that were directly linked to elements in the CPP. These documents allow sharing of knowledge within the project through a central repository used in the project and accessible to all project participants as an ad hoc version of a technology wiki approach (Levandowski et al., 2012).

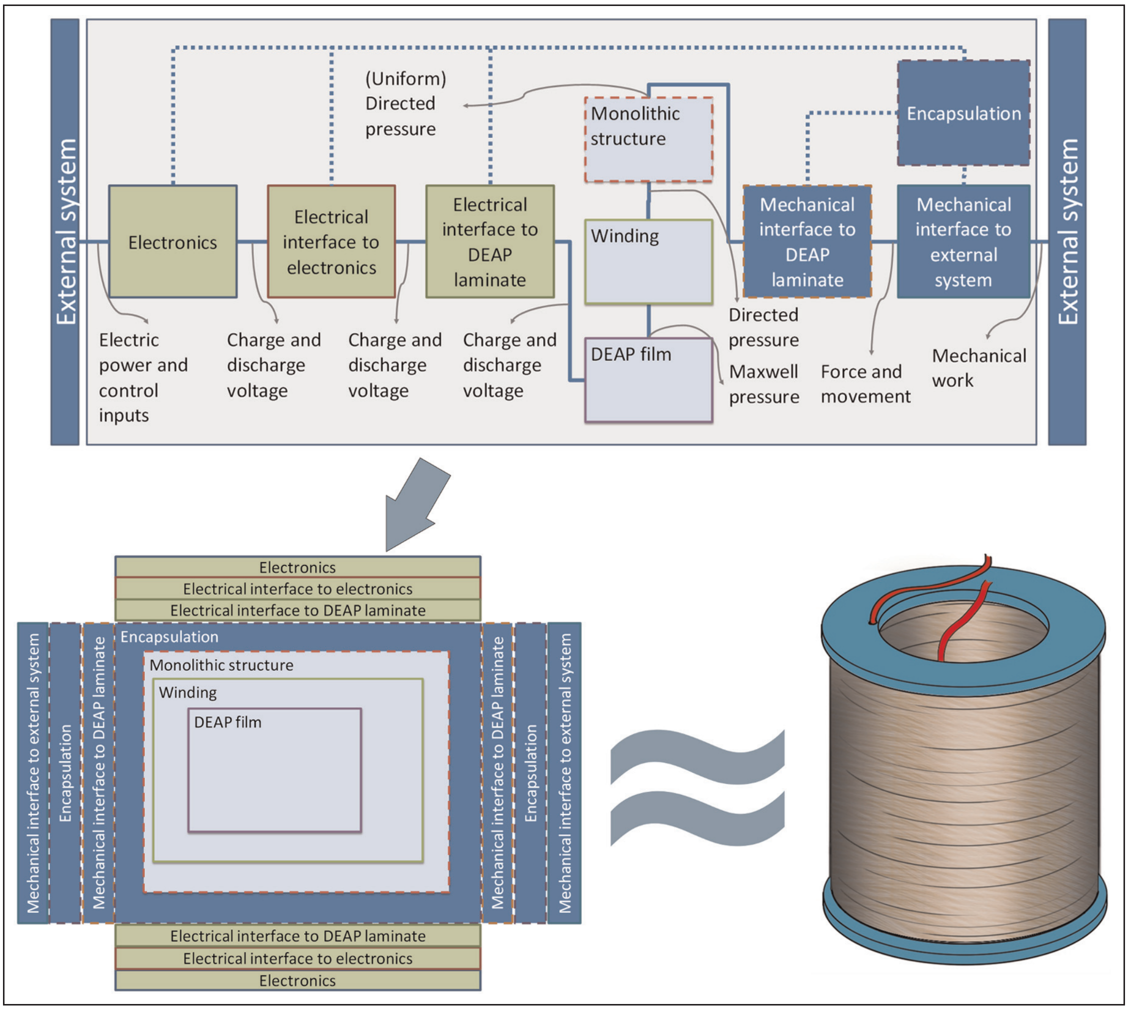


Figure 3. A generic organ diagram (top) for an EAP transducer and an alternative visualization of an organ diagram (bottom left), which is a graphic representation of an EAP transducer from the case project. An EAP linear actuator of type Axial I is shown for comparison (bottom right).
EAP: electro-active polymer; DEAP: dielectric electro-active polymer.

Experiences from using the tool in the EAP case

The CPP model, in the form of a large format poster, was extensively used during meetings as a communication tool, both as an overview and during more focused discussions on the tasks regarding specific organs and organ alternatives. It provided participants with a reminder of the contents of other tasks, while these were being discussed, and acted as a tool to ensure that all attendees were aligned in their perception of particular organ alternatives, application requirements, or other facets of the development work depicted in the CPP model. The physical format of the CPP model allowed participants to add to this model during meetings, or to mark and change existing information, based on input acquired during the meeting. The CPP model was then electronically updated accordingly after the meeting.

Concept evaluation and elimination were performed using the CPP. Multiple concepts in the CPP were able to fulfill the same application requirements, and concept reduction was based on their ability to fulfill multiple application requirements and their sharing of organ alternatives. This allowed the technical solution space to be reduced, without impacting the platform's ability to fulfill application requirements, and ensured that technical solutions were decoupled from individual applications as the uncertainties around EAP transducer applications were still significant.

The CPP model has also been used as a communication tool toward parties outside of the team working on the platform. The recipients can be split into four main groups: participants from platform development work package, project participants from other work packages, members of the steering committee, and customers visiting DPP. Table 1 shows an overview of the

Table 1. The CPP model has been used as a communication tool toward the four groups of recipients.

	Communication form	Utilization dimension
Participants from platform development work package	A poster showing that the CPP model has been hung on the wall during meetings with other work packages	Track performance goals for organ alternatives Link development tasks within the platform to application context and to other work packages Provide a platform perspective during discussions on tasks within platform development Decide focus of organ alternative development tasks based on design rationale Evaluate the contribution of organ alternatives to the platform to make decisions on which development tasks to continue and discontinue
Participants from other work packages	A poster showing that the CPP model has been presented during meetings with other work packages and hung on the wall during meetings with other work packages	Present platform contents and capabilities Link development work in the other work packages to the platform development to identify performance factors for platform Communicate platform capabilities during concept development for key applications
Steering committee	Parts of the CPP model have been presented in presentations at steering committee meetings to provide an update of the progress in the development of the project	Prioritize focus areas and resources within the DNATF DEAP project Evaluate platform potential and platform development work with focus on platform capabilities and feasibility of development work
Customers visiting DPP offices	The CPP model has been presented to visitors to DPP offices, both customers and potential customers	Present platform contents and capabilities Discuss potential platform solutions for customer's application

CPP: Conceptual Product Platform; DNATF: Danish National Advanced Technology Foundation; DEAP: dielectric electro-active polymer; DPP: Danfoss PolyPower.

four recipient groups, the form of communication, and the reception of the communication.

The extensive use of hand-sketched illustrations to communicate product and application concepts, organ alternatives, and technical principles was well received by the project team. Some project members were not well acquainted to using hand sketches as a communication tool, but have expressed their appreciation of the sketches' ability to communicate ideas while indicating that the ideas are not fully developed.

The generic organ diagram was not well received by the team members. The team members felt it was too abstract and did not represent their idea of an EAP transducer. The alternative illustration that includes all the same organs, but has a more direct link to the EAP transducers, was received better by the team members; they could identify the revised graphic as a representation of an EAP transducer, and discussions about the diagram could focus on the tasks at hand, rather than the formatting of the diagram.

Conclusion

The main contribution of this work is the CPP model. The CPP model has provided operational support to mechanical platform development within a real-life industrial technology–push project aimed at maturing and commercializing a novel technology. The CPP has supported the development through the identification and organization of organ alternatives, evaluation and selection of product concepts based on application requirements, as well as providing an overview of the platform, its contents, and its links to the intended applications.

By providing an overview of organ alternatives, it has supported the communication of development tasks and their status and decisions on the continuation of development tasks. The link to the intended applications provided the technical development team with a context for what was required of the technical solutions being developed and a measure of what provides value to the intended applications—providing a decision base for platform contents. The CPP model has furthermore proved a valuable communication tool toward the development team, project collaborators, management stakeholders, and potential customers.

The case study has shown that the use of a visual model in a physical medium that could be updated during meetings helped to ensure that the model showed the current state at all times and that relevant stakeholders were aligned in their perceptions regarding the development tasks.

Further work that could be relevant to this research includes applying the CPP model on a broader scale, for example, by including other technical domains such as electronics or in cases with other participants.

Acknowledgements

The authors would like to thank all project partners and the project's steering committee for providing input to this research. The valuable input of reviewers is also gratefully acknowledged.

Declaration of conflicting interests

The authors declare that there is no conflict of interest.

Funding

This work was financially supported by the Danish National Advanced Technology Foundation.

References

Andreasen MM (1980) *Syntesemetoder på Systemgrundlag—Bidrag til en konstruktionsteori*. PhD Thesis, Lund Institute of Technology, Lund.

Andreasen MM and McAloone TC (2008) Applications of the theory of technical systems—experiences from the "Copenhagen School." In: *Proceedings of AEDS 2008 workshop*, University of West Bohemia, Pilsen, Czech Republic, October 31–November 1, 2008, pp. 1–18.

Bruun H and Mortensen N (2012) Visual product architecture modelling for structuring data in a PLM system. In: Rivest L, Bouras A and Louhichi B (eds) *Product Lifecycle Management: Towards Knowledge-Rich Enterprises.* : IFIP WG 5.1 International Conference, PLM 2012, Montreal, QC, Canada, July 9–11, 2012, Revised Selected Papers. Berlin: Springer Berlin Heidelberg, pp. 598–611.

Checkland P and Holwell S (1998) Action research: its nature and validity. *Systemic Practice and Action Research* 11(1): 9–21.

Christensen C (1998) *Du Pont Kevlar Aramid industrial fiber (abridged)*. Harvard Business School Case 9-698-079, Harvard Business School Publishing, Boston, MA, May, pp. 1–10.

Dewar RD and Dutton JE (1986) The adoption of radical and incremental innovations: an empirical analysis. *Management Science* 32(11): 1422–1433.

Eppinger SD and Browning TR (2012) *Design Structure Matrix Methods and Applications* (Engineering Systems). Cambridge, MA: The MIT Press, p. 352.

Ernst Eder W (2011) Engineering design science and theory of technical systems: legacy of Vladimir Hubka. *Journal of Engineering Design* 22(5): 361–385.

Gero JS (1990) Design prototypes: a knowledge representation schema for design. *AI Magazine* 11(4): 26–36.

Gershenson JK, Prasad GJ and Zhang Y (2003) Product modularity: definitions and benefits. *Journal of Engineering Design* 14(3): 295–313.

Guðlaugsson TV, Mortensen NH and Sarban R (2013) EAP high-level product architecture. In: *Proceedings of SPIE 8687, Electroactive Polymer Actuators and Devices (EAPAD)* (ed Y Bar-Cohen), San Diego, CA, 10–14 March, pp. 868710-1–868710-8. Bellingham, WA: SPIE—International Society for Optics and Photonics.

Hansen CB (2013) Cooperating or conflicting values? *Paper presented at the 11th public management research conference*, Madison, WI, 20–22 June, pp. 1–47. Public Management Research Association. Lawrence, Kansas.

Harlou U (2006) *Developing product families based on architectures*. PhD Thesis, Technical University of Denmark, Kongens Lyngby.

Holt J, Perry SA and Brownsword M (2012) *Model-Based Requirements Engineering*. London: The Institution of Engineering and Technology, pp. 4–6.

Hölttä K and Salonen M (2003) Comparing three different modularity methods. In: *ASME 2003 international design engineering technical conferences and computers and information in engineering conference* DETC2003/DTM-48649, Chicago, IL, 2–6 September, pp. 533–541. New York: ASME.

Hubka V and Eder WE (1988) *Theory of Technical Systems—A Total Concept Theory for Engineering Design*. Berlin: Springer-Verlag.

Jiao J and Tseng M (2000) Understanding product family for mass customization by developing commonality indices. *Journal of Engineering Design* 11(3): 225–243.

Johannesson H and Claesson A (2005) Systematic product platform design: a combined function-means and parametric modeling approach. *Journal of Engineering Design* 16(1): 25–43.

Kano N (1995) Upsizing the organization by attractive quality creation. In: Kanji GK (ed.) *Total Quality Management: Proceedings of the first world congress*. Chapman & Hall, London, UK. pp. 60–72.

Kvist M (2009) *Product family assessment*. PhD Thesis, Technical University of Denmark, Kongens Lyngby.

Levandowski CE, Corin-Stig D, Bergsjo D, et al. (2012) An integrated approach to technology platform and product platform development. *Concurrent Engineering: Research and Applications* 21(1): 65–83.

Mankins JC (1995) Technology readiness levels. White Paper, Advance Concepts Office, Office of Space Access and Technology, NASA, Washington, DC, 6 April, p. 5.

Marion TJ and Simpson TW (2006) Platform leveraging strategies and market segmentation. In: Simpson TW, Siddique Z and Jiao JR (eds) *Product Platform and Product Family Design*. New York: Springer Science + Business Media, pp. 73–90.

Martin M and Ishii K (2002) Design for variety: developing standardized and modularized product platform architectures. *Research in Engineering Design* 13(4): 213–235.

Meyer MH and Lehnerd AP (1997) *The Power of Product Platforms*. New York: Free Press, pp. 1–288.

Mortensen N (1999) *Design modelling in a designer's workbench: contribution to a design language*. PhD Thesis, Technical University of Denmark, Kongens Lyngby, p. 192.

Mortensen N and Hvam L (2011) Improving decision making in the early phases of configuration projects. *International Journal of Industrial Engineering* 15(2): 185–194.
Nasiriyar M and Jolly D (2007) Technology platform exploitation: definition and research boundaries. In: *16th international conference on management of technology*, Miami Beach, FL, 13–17 May.
Nieto M, Lopéz F and Cruz F (1998) Performance analysis of technology using the S curve model: the case of digital signal processing (DSP) technologies. *Technovation* 18(6–7): 439–457.
Pedersen R (2010) *Product platform modeling: contributions to the discipline of visual product platform modelling*. PhD Thesis, Technical University of Denmark, Kongens Lyngby.
Prasad B (1996) *Concurrent Engineering Fundamentals: Integrated Product and Process Organization*. Upper Sadle River, NJ: Prentice Hall PTR, pp. 1–478.
Rosenman MA and Gero JS (1994) The what, the how, and the why in design. *Applied Artificial Intelligence* 8: 199–218.
Sanchez R (2000) Modular architectures, knowledge assets and organisational learning: new management processes for product creation. *International Journal of Technology Management* 19(6): 610–629.
Sanchez R (2004) Creating modular platforms for strategic flexibility. *Design Management Review* 15(1): 58–67.
Sanchez R and Collins RP (2002) Competing—and learning—in modular markets. *Long Range Planning* 34: 645–667.
Schachinger P and Johannesson H (2000) Computer modelling of design specifications. *Journal of Engineering Design* 11(4): 317–329.
Shapiro AR (2006) Measuring innovation: beyond revenue from new products. *Research Technology Management* 49(6): 42–51.
Stone RBR, Wood KLK and Crawford RHR (2000) A heuristic method for identifying modules for product architectures. *Design Studies* 21: 1–47.
Tryson M, Kiil H-E and Benslimane M (2009) Powerful tubular core free dielectric electro activate polymer (DEAP) push actuator. In: *Proceedings of the SPIE 7287, Electroactive Polymer Actuators and Devices (EAPAD)* (ed Y Bar-Cohen and T Wallmersperger), San Diego, CA, 8 March, pp. 72871F-1–72871F-11. Bellingham, WA: SPIE.
Ulrich K (1995) The role of product architecture in the manufacturing firm. *Research Policy* 24(3): 419–440.

Author biographies

Tómas V Guðlaugsson is a PhD student at the section of Engineering Design and Product Development at the Mechanical Engineering Department at the Technical University of Denmark (DTU), Denmark. He has a MSc in Design and Innovation from DTU. His research is focused on the development of platforms in conjunction with technology development.

Poul M Ravn is a PhD Student at the section of Engineering Design and Product Development at DTU. He holds an MSc in Design & Innovation from DTU. His current research is on multi-product integration in technology development.

Niels H Mortensen holds a PhD and a MSc in Mechanical Engineering and is employed as a Professor at DTU. He is head of the section of Engineering Design and Product Development at DTU Mechanical Engineering at DTU. His main research focus is procedures and methods supporting development of Product Families based on Architectures and Platforms. Currently, there are nine researchers within the field of architecture-based product development at the section.

Rahimullah Sarban Rahimullah Sarban received his MSc in Mechatronic Engineering in 2008 and his PhD in 2011 from University of Southern Denmark. Rahimullah was employed as project manager in Danfoss PolyPower A/S, with the project goal being development of a technology platform architecture. Rahimullah is now Director and Partner at LEAP Technology – an EAP product development company which he co-founded in April 2014.

APPENDIX F

Paper F

Visual modelling of pilot production to support decision making in production development

Poul Martin Ravn, Tómas Vignir Guðlaugsson, Niels Henrik Mortensen

Published in the proceedings of the 13th International Design Conference DESIGN 2014, Dubrovnik, Croatia.

INTERNATIONAL DESIGN CONFERENCE - DESIGN 2014
Dubrovnik - Croatia, May 19 - 22, 2014.

VISUAL MODELLING OF PILOT PRODUCTION TO SUPPORT DECISION MAKING IN PRODUCTION DEVELOPMENT

P. M. Ravn, T.V. Guðlaugsson, N.H. Mortensen

Keywords: Decision making, visual modelling, pilot production

1. Introduction

Industrial production faces a challenge of optimisation in almost every aspect, to live up to the continuous demand of increased capacity. Some of the production process issues that are under continuous focus include dimensional tolerances and surface finish, production quantity, production rate, lead time, and robustness and process [Kalpakjian and Schmid 2006]. However, before this can be achieved, the production processes need to be matured to a point where product quality requirements and production capacity needs can be met. When the product to be produced is based on a new technology, never produced in large quantities before, the first priority is to prove that it can be produced at all.

As a central part in production process development, a pilot production can be used as a prototype for the production process, where the processes can be developed, tested, and refined [Oberle 2013]. To be successful, a pilot production should first and foremost be able to demonstrate that the intended products can be produced to the required quality levels. Here, the focus is on achieving control of individual processes, demonstrating scalability of critical production processes, implications of process parameters on product characteristics, and weaving out critical faults in production processes, to a level where the results can provide a foundation for decisions on investing in a full capacity production facility [Oberle 2013]. Therefore, making the right decisions in the pilot production can be crucial for the success in production process development.

A common way of supporting decisions in production is to capture the production process design with a desired perspective. Production process modelling has been done for decades with flowcharts [Gilbreth and Gilbreth 1921], and a large number of different other tools, and most tools are found to be aimed for communicating specifics about the process for further analysis. Most process modelling approaches are aimed to support industrial production and thus highly standardized. Visual modelling approaches have previously been shown to support decision making in production process development projects [Alabastro et al. 1995] and product development projects [Mortensen et al. 2008]. This paper presents the practical experiences from supporting and communicating the decision making for a pilot production setup in a technology development project by visual modelling. The modelling is based on the generic production flow [Mortensen et al. 2011], but in a setting where neither product nor production is yet defined. These results are part of research into the application of visual modelling tools to support decision making in production process development.

The paper is structured as follows: Section 2 highlights and discusses production process modelling methods found in literature and industry. Section 3 presents a case, in which production of a new technology is being developed in order to demonstrate that production of a new Electro-Active-Polymer (EAP) film technology can be scaled, while increasing production quality and EAP film performance. Section 4 presents findings in the case. Section 5 discusses the findings and presents future work. Section 6 presents the conclusion of the paper.

2. Production modelling approaches

This section will review some production modelling approaches found in literature and industry today and discuss their application. The focus will be on diagrammatic modelling approaches [Vergidis et al. 2008].

Flow charts are one of the simplest ways to graphically model production processes [Meyer et al. 2006]. In their most basic form, they comprise no graphical elements other than standardized flowchart symbols, which give no detailed information on the processes that they depict. Within the processing industry, process flow diagrams include standardized abstract graphical symbols to denote important processes and equipment [Silla 2003]. Although they provide more graphical information to the reader, a full understanding of the production process depicted cannot be achieved without knowledge of the symbols, and the processes represented by them. This reduces their effectiveness when they are used to communicate the production process to persons unfamiliar with the symbolism or that lack specialist knowledge of the processes.

The Integration Definition (IDEF) suite and the Unified Modeling Language (UML) have been demonstrated for modelling of production process design [Perera and Liyanage 2000] [Zhang et al. 2007]. Where IDEF has been developed and applied over a number of decades [Spur et al. 1996], the UML is a more recent approach. Both make use of a number of different diagram types to model distinct aspects of a system, but only with standard, graphically simple, notations defined for each modelling approach. Their application to modelling production systems in detail has been shown, from different perspectives, and they are often used in conjunction with process simulation tasks. [Oscarsson and Moris 2002]

The generic production flow is a visual modelling approach that has been used in the development of product platforms and families [Mortensen et al. 2011]. The generic production flow visualises the production flow for product variants, through visual modelling of process steps and the resulting output, as well as identifies common process steps. One of the experiences from the application of the model, together with product and market architectures, was reported to be “Improved synchronization between product- and production development.” [Mortensen et al. 2011, p. 1] The utilisation of the generic production flow has proved beneficial in the context of product families, but the flow model has not been investigated for use in a pilot production setup.

For the application of most modelling principles, a number of general considerations have to be made. The level of detail to be captured in the model should be defined. The purpose of the modelling should be defined, so the model covers the needs from the users of the model. Considerations about what points in time that should be captured are beneficial. Some projects may have interest in defining the current situation, where others may gain from modelling desired, future setups. [Browning 2010]

Visual modelling using graphical elements, icons, to depict process equipment, as part of a simulation model development, has been shown to benefit understanding across knowledge domains and increase commitment from stakeholders [Alabastro et al. 1995].

The generic production flow has been used successfully within product-family development and includes a focus on product variant creation. In the pilot production development of focus in this paper, the ability to produce product variants, and the determination of product characteristics in the production process, is of a high priority. The generic production flow is therefore a solid foundation to build upon for this purpose.

3. Case: visual modelling of the EAP film production

The production of a new technology is being developed by Danfoss PolyPower in order to demonstrate that production of a new Electro-Active-Polymer (EAP) film technology can be scaled, while increasing production quality and EAP film performance [Kiil 2009]. The production of the EAP film has through the past ten years gone from lab production setups to a pilot production setup with the goal of reaching a matured EAP production setup capable of mass-producing the EAP film.

Danfoss PolyPower has, together with a consortium of companies and universities in Denmark, defined a five year, 12 million € project supported by the Danish National Advanced Technology Foundation (DNATF), to mature the EAP technology. The project includes multiple work packages working in parallel to develop materials, production processes, products, mathematical modelling, and prototypes for applications of EAP future products. The modelling task described in this case was initiated by the project manager, accommodating wishes from the case project steering committee, to support the management of the tasks involved with production process development in the project, and the implications on the production. The decision was to model the pilot production setup, with the intended developments in the DNATF project, to support the communication between collaborators and decision-making in production process development tasks.

3.1 Method

The development of the model was carried out in three draft phases, with the drafts reviewed through workshops; the final draft was presented at a project symposium. Figure 1 shows the process followed in the case study and highlights major phases in the development of the model: draft work on the model, workshops for discussion and verification, and feedback. To create a frame for gathering the required data needed for the modelling, with a verified content, data triangulation was used [Yin 2009]. Different sources of evidence were used for data triangulation: documents (previous production process diagrams), interviews (with production manager and production team), and participant observation (as active contributors in the workshops). Workshops were used to involve the production team in the development of the model and to make the progression visible.

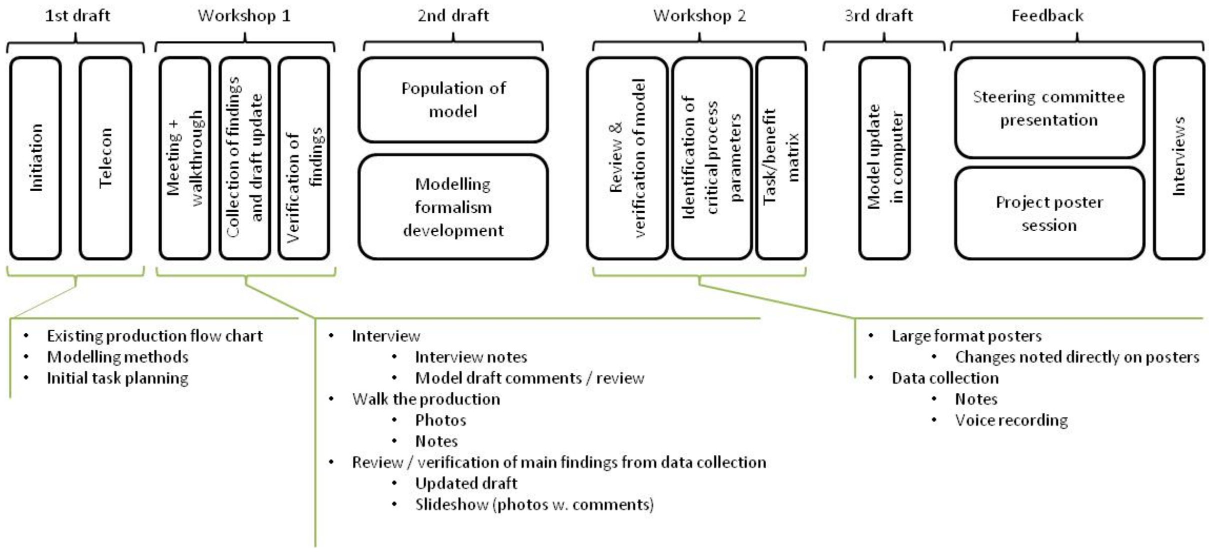


Figure 1: The process followed in the case project, to develop the model.

3.1.1. Draft iterations

The initial draft phase involved analysis of existing product process diagram, modelling methods in literature, alignment of expectations between researchers and production manager, and task planning. Subsequent draft phases comprised the main efforts in developing the modelling formalism and modelling elements, which were developed in parallel with population of the model and illustration activities.

3.1.2. Workshop 1

The aim of workshop 1 was to gain a detailed understanding of the production processes to be modelled. This workshop involved data collection activities. An interview was held with the production manager, where a draft model of the production formed a basis for discussions and was commented on by the production manager and researchers. During a walkthrough of the production with the production manager, photos and notes provided the main data collection method. Photo management software was used to produce a slideshow of the photos from the walkthrough with comments by the researchers on the processes depicted by the photos. The slideshow was used, along with an updated version of the draft model, to verify the findings during a review with the production manager.

Figure 2: A large-format poster was used during workshops to facilitate active discussions and enable ‘on-the-fly’ changes to the model.

3.1.3. Workshop 2

Workshop 2 involved, on behalf of the case company, the production manager, the project manager, and two process engineers. At the workshop four posters were utilized, one large format version of each production process to be modelled (past, current, future), and a production overview poster that included all modelling elements (see Section 3.2.1). The overview model was reviewed with the participants, during which comments and questions for discussion were welcomed and, if possible, noted directly onto the poster (Figure 2). Each of the process steps in the production was reviewed in detail to collect information on critical parameters for processes, accuracy of the model, and detail level. The workshop was concluded by reviewing a task-benefit matrix, showing how process improvement tasks within the project were linked to benefits in production performance or quality, and an update of the roadmap for production tasks.

3.1.4. Feedback

The production overview poster was presented by the production team to two recipient groups; the steering committee of the case project during a review and participants from other parts of the case project consortium. Feedback after the case was collected from the production manager and the project manager through interviews.

3.2. The developed model

The production overview, shown in Figure 3, was used to communicate the primary issues of the production development within the case project. The aim of the modelling task was to highlight the intended benefits of production equipment developments and investments, communicate the decisions to be made during the development of the pilot production, communicate the resulting output of key processes, identify where product characteristics are realized in the production process, and communicate the production process design to multiple recipients at different levels in the organization.

The main modeling was done in Microsoft® Visio®, as it was used for the previous flow modeling of pilot production in the company.

3.2.1. General overview

The production overview developed comprises four main sections.

Vision - A graph illustrating the vision of the increase in capacity communicates the aim of demonstrating production scalability. This is linked to (1) the material development progress and (2) the knowledge, and experience, regarding control over the production setup and processes.
Production process - Three production process models of the production, in initial (previous, 2011), present (current, 2013) and projected (future, 2015), respectively. Each production process model instance, in Figure 3 (2011, 2013, and 2015) shows a model of the production process at the respective time in the project. The details of the production process models are elaborated in section 3.2.2.
Roadmap - A roadmap shows the production process development tasks on a timeline, to illustrate the completed, current and ongoing tasks. The roadmap showed parallel development tasks aimed at improvements in all process steps.
Benefit of improvements - A task-benefit matrix shows what benefits or capabilities that completed production process development tasks will enable, in a number of dimensions, e.g. performance or product quality. The matrix showed that some benefits were realized by not only one task, but multiple tasks. Many of the tasks were also linked to multiple expected benefits.

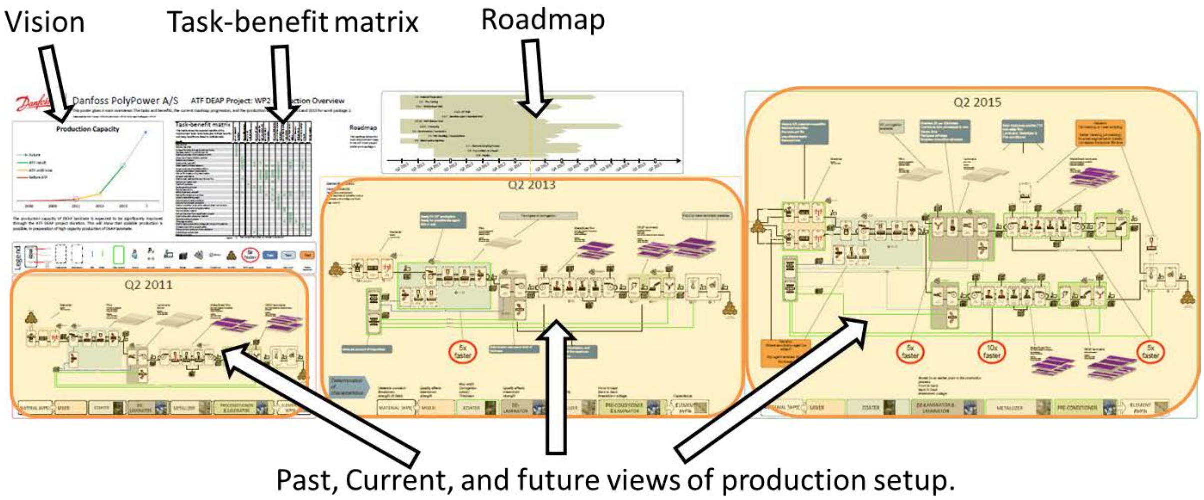


Figure 3: Production overview poster from case project.

3.2.2. The production process models

The production process models share the same modelling formalism. Figure 4 shows part of the production process model for 2013, along with selected modelling elements used in the modelling formalism to denote important issues. The production process models communicate the following aspects:
The process flow - Each of the process steps are illustrated by a rounded rectangle with a principle illustration to show the function of the process to aid communication to a wider audience. In addition, critical process parameters are noted for each process. The border of the rounded rectangle is used to indicate those cases where the process is implemented but not used or where a decision needs to be made for the particular process. The main difference, as opposed to the generic production flow model, is the focus on the processes and their critical parameters, their change over time, and their ability to create output variants, instead of identifying variant creation points within a defined product family.
Storage and transport - Storage and transport means between stations is illustrated, by graphical icons, to enable future analysis and optimizations of the production setup e.g. in relation to production scale-up.
Main stations - The main stations (machines) utilized in the film production are noted at the bottom of each model and as shaded backgrounds in the production process model. The colour of the shading links the two representations. The border of the rounded rectangle is used to indicate, those cases where the process is new.

Resulting output - The resulting output of each main station, in terms of film variants, is illustrated by CAD illustrations, highlighting where in the processes the variants are defined in the production.
Process time - Two types of information on processing time are communicated in the models. The processing time for a single batch of a certain size, is noted for each main workstation. An estimation of how many times faster a process will become with a planned upgrade from the roadmap is noted by a red circle for each workstation improved, for the particular production process model instance.
Critical decisions - Decisions to be made on workstations or processes are noted on the production process model. For each critical decision, the known alternatives and implications are noted concisely.
Achieved characteristics – At the bottom of each production setup view, the main stations of the production are modelled, with film characteristics noted. This links the achieved film characteristics to the main process steps, indicating where changes should occur in production to affect film characteristics.
.

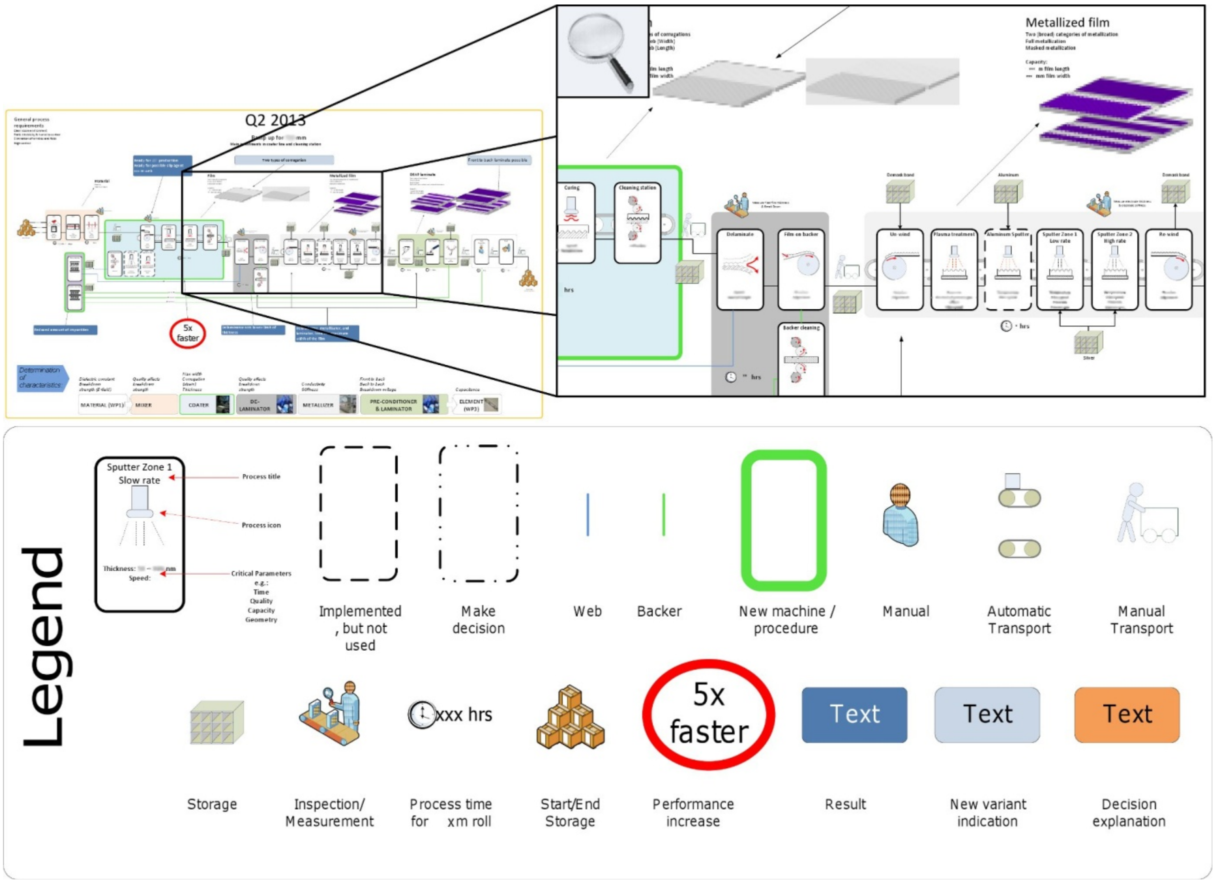


Figure 4: Part of the production model of current production (top). Legend of the modelling formalism (bottom).

4. Findings

The findings reported here stem mainly from the workshops, as observations, and from feedback interviews with the project manager and the production manager. Findings on the modelling process, as well as the use of the model for internal and external communication by the production team are treated in this section.

4.1. The modelling process

Using a commented slideshow presentation of photos to verify findings during workshop 1 was found to be a strong tool to create discussions and highlight the overall flow, and details, in a visual manner.

This reduced the amount of misconceptions after the first workshop, thus reducing the resources required to reach an accurate model of the production.

Bringing large-format print-outs, A0 or larger, of the model to workshops was found to be a crucial aspect in discussing the contents of the model, as well as noting comments, changes and suggestions ‘on-the-fly’. The large format allowed the whole team to see details on the model and contribute to the session (see Figure 2). Bringing the production team together to discuss the models had a positive effect on bringing up issues regarding the production process development. The production team initiated discussions during workshop 2 to reflect on implications of new machinery, improvements of processes, and identification of critical process parameters.

The task-benefit matrix captured many of the links between intended benefits from the project and the production process development tasks in the project. The critical process parameters could be noted directly on the production process models, as well as implications of decisions on processing equipment or process flows.

Visualising the production process steps for the production team enabled them to ‘show’ the core of the process and how it is linked to the characteristics of the products; knowledge that was previously only found within the minds of the production team members. This link between the characteristics of production and production output (in this case the DEAP film) allowed the team to reason about future updates and predict what effect changes would have on the film. At the end of workshop 2 it was discussed by the team, whether it should be used for presentation of the production setup to an external vendor, as they saw it as a tool to provide the external vendor with a greater understanding of their production process.

4.2. Communication within the production team

The overview brought by the model, and the level of details in it, ensures that the production team is aware that they also need to keep ‘this and that’ in mind, when considering the production process. In interviews it was stated, that the visualisation, as opposed to standardized flow charts, made it easier to ‘see’ how a change in one process would affect further down the process flow. The model is therefore used whenever pros and cons of suggested process changes are discussed within the production team. The model effectively communicates what the activity is, what the process is, and what is critical. The link to what output variants are realized and what product characteristics are determined, by the process, shows what the purpose of the production process is.

The task-benefit matrix was intended to highlight what the different tasks/improvements would help on in the production, but when interviewed for feedback, the production manager stated that the team used the flow-models for discussions on improvements and the project manager stated that the full potential of the matrix was yet to be realised.

4.3. Communication outside the production team

The modelling task was considered to have fulfilled the goals of the steering committee, which initiated the task.

The model has been used to communicate the production process to parties outside the production team, both within the business unit and collaborators in the DNATF consortium. The production team has experienced the use of the model as beneficial for their ability to explain the process to external parties. Here, the graphical elements play a large role, according to the project manager, in explaining the production process to stakeholders that are not deeply involved with the production process. This was also viewed as an indicator that the model was a success by the project manager. That the production team could use the model, and explain it; especially that they could use it to explain to others what the production process, and its development, is all about.

The production manager has the intention of keeping the models updated for further use, as the production process models eased communication of the production process to parties both inside and outside of the production team.

For communication to persons outside the business unit, it was stated, that the overview may contain too detailed information, but for discussion within the production team the overview had a fitting level of detail. It was, however, also noted by the production manager that it is easier to reduce the detail level for another recipient, than it is to increase the detail level.

5. Discussion and future work

There may be limitations to implementing the presented model in industry. The modelling formalism does not adhere directly to current practices in production models, frequently used by production managers and often integrated into PLM systems. Therefore, multiple models might need to be kept up to date in some companies, if this modelling was adopted. The present model, although based on models and approaches previously tested in industry, has only been implemented in an early stage production development, with a new product and new production. Its application within a more mature industrial setting has not been investigated.

In the EAP case, it was found through the interviews that the visual model presented the production team with a high amount of detail. This was reported to be of little matter, as the visual approach helped the team in the current phase of defining the production process. At a later stage, the model can be used as a base for a standardised flow chart, when the main process setup is in place, should a standard flow chart be preferred at that stage.The level of detail in the model was a result of the data collection and the extended generic production flow model formalism. As to the aim of having a model that allowed for communication with multiple recipients at different levels, the model has introduced an increase in detail when compared to the existing flow chart in the case. The aspect of communication internally in the production team and with externals revealed two different dimensions to be taken into account, an overview request driven by manager level, and detail request, driven by the expert team. This matter might be resolved in some cases by introducing layers, defined in the software, which allows details to be hidden for some recipients while using the same document. It is, however, an aspect that should be considered carefully, as adding layers may add detail as well as create confusion when deciding to what layers new changes shall apply. It is important to underline the fact that the main observations on the use of the model was made on printed versions of the model, not the virtual model. Further research on the use of the model in regards to updates, changes etc. would need to be investigated to evaluate the daily use of the model. As the developed model does not follow standard practises within companies to model production processes, finding employees that are comfortable with keeping the model updated may be an issue. However, the software used is readily available, relatively well known in industry, and often used for flow models in industry.

The model presented in this paper is not intended to work as a total definition of the production setup – it is intended to provide an overview of key factors to support discussions and decision-making, and its fitness to other purposes depends on its alignment with those purposes [Browning 2010]. The visual model has its strength in providing overview, details, and means for communication, in a technology pilot production. The applicability of this modelling formalism within established industrial production has not been investigated in this case.

The EAP film production is only a part of the production of an EAP transducer. Harlou [2006] emphasises the alignment between market, product and production architectures, as adapted in Figure 5. Within the DNATF project, the definition of transducer types is ongoing, supported by the Conceptual Product Platform (CPP) [Guðlaugsson et al. 2013], which looks into the market and product family views, and a system architecture modelling approach for support of the integration in test applications of the EAP, as illustrated in Figure 5. The work done with the CPP feeds into the definition of EAP transducer type definition. To support the transducer production, the proposed modelling approach can be further expanded, to support design decisions for the production of EAP transducers with links to the EAP transducer architecture from the CPP.

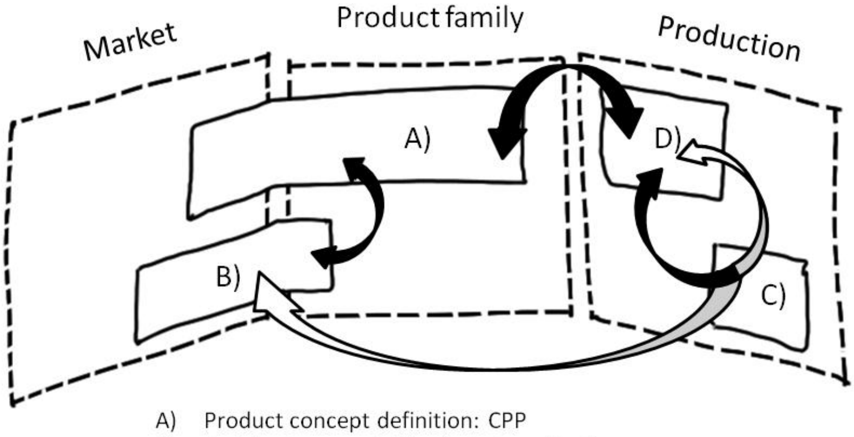


Figure 5 – Linking market definition, concept definition and production definition. Black arrows represent content links and light arrows represent modelling formalism links. Market, product family, and production views adapted from Harlou [2006].

6. Conclusion

A visual production model, based on the generic production flow has been developed for a pilot production in a technology development project of EAP film. The model has been well received by the production team and is being used both for internal communication and communication outside the team to illustrate the decisions, future changes, and the links to both an upcoming EAP component platform as well as the visual modelling of systems with which the EAP is being integrated. The visual model supported the management of tasks involved with production process development in the project, by fulfilling the following aims:

- Identify benefits of production equipment developments
- Communicate decisions during development of pilot production
- Communicate the resulting output after key processes
- Identify where in the production process, product characteristics are realised.
- Communicate the production process design to multiple recipients at different levels.

The method has given suggestions to the process of documenting the production in an early setup and the findings from the case project indicate that workshops on documenting the production process can help make the tacit knowledge of stakeholders explicit. The follow-up feedback stated, that the modelling was a help in the daily work in the production team.

Acknowledgement

The presented work was carried out at the Technical University of Denmark and at Danfoss PolyPower. We would like to thank the Danish Advanced Technology Foundation for part funding of the research program at the Technical University of Denmark. We would also like to thank Danfoss PolyPower A/S for providing valuable input for the case description.

References

Alabastro, M.S., Beckmann, G., Gifford, G., Massey, A.P. and Wallace, W.A., "The Use of Visual Modeling In Designing a Manufacturing Process for Advanced Composite Structures", IEEE transactions on engineering management, Vol. 42, No. 3, 1995, pp. 233-242.

Browning, T.R., "On the alignment of the purposes and views of process models in project management", Journal of Operations Management 28, 2010, pp. 316-332.

Gilbreth, F.B., Gilbreth, L. M., "Process charts", American Society of Mechanical Engineers, New York, 1921.

Gudlaugsson, T.V., Mortensen, N.H., Sarban, R., ”EAP high-level product architecture”, Proc. SPIE 8687, Electroactive Polymer Actuators and Devices (EAPAD) 2013, Yoseph Bar-Cohen, San Diego, California, USA, 2013, pp. 868710-1 - 868710-8.
Harlou, U., "Developing product families based on architectures", PhD thesis, Technical University of Denmark, 2006.
Kalpakjian, E., Schmid, S.R., “Manufacturing engineering and technology”, Pearson Education, Upper Saddle River, New Jersey, USA, 2006.
Kiil, H.-E., Benslimane, M., “Scalable Industrial Manufacturing of DEAP”. Proc. SPIE 7287, Electroactive Polymer Actuators and Devices (EAPAD) 2009, Yoseph Bar-Cohen, Thomas Wallmersperger, San Diego, California, USA, 2009, pp. 72870R-1 - 72870R-10.
Meyer, U. S., Creux, S. E., & Weber Marin, A. K., “Process Oriented Analysis”, CRC Press, Boca Raton, Fl, USA, 2006, pp. 37–95.
Mortensen, N.H., Pedersen, R., Nielsen, O.F., Harlou, U., Bøgh, M.H., Høgh, P.T., Hvam, L., ”Implementing a product platform in 35 man-days: the visual thinking approach”, International Journal of Mass Customisation, Vol. 2, No. 3, 2008, pp. 240-263.
Mortensen, N.H., Hansen, C.L., Hvam, L., Andreasen, M.M., “Proactive modelling of market, product and production architectures”, Proceedings of the 18th international conference on engineering design: impacting society through engineering design, Vol. 4, Kgs. Lyngby, Denmark, 2011, pp 133-144.
Oberle, T., ”Process techniques for engineering high-performance materials“, CRC Press, Boca Raton, Fl, USA, 2013, pp. 235–272.
Oscarsson, J., Moris, M.U., “Documentation of discrete event simulation models for manufacturing system life cycle simulation”, Proceedings of the 2002 Winter Simulation Conference,Vol. 2, Yucesan, E., Chen, C.H., Snowdon, J.L., and Charnes, J.M., eds., San Diego, California, USA, 2002, pp. 1073-1078.
Perera, T., Liyanage, K., “Methodology for rapid identification and collection of input data in the simulation of manufacturing systems”, Simulation Practice and Theory 7, 2000, pp. 645-656.
Silla, H., “Chemical Process Engineering: Design and Economics”, Marcel Dekker, Inc., New York, NY, USA, 2003, pp. 1–28.
Russel, R., Taylor, B., “Operations Management”, 7th edition, International Student Version, John Wiley & Sons, Inc., Hoboken, New Jersey, USA, 2011.
Spur, G., Mertins, K., Jochem, R., “Integrated Enterprise Modelling”, Beuth Verlag GmbH, Berlin, DE, 1996.
Vergidis, K., Tiwari, A., Majeed, B., ”Business Process Analysis and Optimization: Beyond Reengineering”, IEEE Transactions on Systems, Man, and Cybernetics - Part C: Applications and Reviews, Vol. 38, No. 1, 2008, pp. 69-82.
Yin, R. K., “Case Study Research”, Sage Publications, Thousand Oaks, California, USA, 2009.
Zhang, L., Jiao, J., Helo, P.T., “Process platform representation based on Unified Modelling Language”, International Journal of Production Reseach, Vol. 45, No. 2, 2007, pp. 323-350.

Poul Martin Ravn
PhD Researcher
Technical University of Denmark, Department of Mechanical Engineering
Produktionstorvet, Building 426B, Kgs. Lyngby, Denmark
+45 45256204
pmrav@mek.dtu.dk
http://www.mek.dtu.dk

Tómas Vignir Guðlaugsson
PhD Researcher
Technical University of Denmark, Department of Mechanical Engineering
Produktionstorvet, Building 426B, Kgs. Lyngby, Denmark
+45 45256253
tomg@mek.dtu.dk
http://www.mek.dtu.dk

APPENDIX G

Paper G

Modelling production architectures in the early phases of product development
Tómas V. Guðlaugsson, Poul M. Ravn, Niels H. Mortensen, Lars Hvam

Submitted to a peer-reviewed journal Note: This is the submitted version. The format was adjusted to single line spacing.

Modelling production architectures in the early phases of product development

Tómas V. Guðlaugsson[A*], Poul M. Ravn[A], Niels H. Mortensen[A], Lars Hvam[B]

[A]*DTU Mechanical Engineering*
Engineering Design and Product Development
Technical University of Denmark

[B]*DTU Management Engineering*
Operations Management
Technical University of Denmark

[*]Corresponding author
Building 426
2800 Kgs. Lyngby
Denmark
Email: tomg@mek.dtu.dk

This article suggests a framework for modeling a Production Architecture (PA) in the early phases of product development. The challenge in these phases is that the products to be produced are not completely defined and yet decisions need to be made early in the process on what production capabilities are needed and appropriate to enable determination of obtainable product quality.

In order to meet this challenge a modeling framework is suggested, one that clarifies which product and production features are known at a specific time of the project and which features will be worked on – leading to an improved basis for prioritizing activities. Requirements for the framework are presented and literature on production and system models is reviewed. The PA modeling framework is founded on approaches in literature and adjusted to fit an early phase of development. The PA models capture and describe the structure, capabilities and expansions of the PA.

The framework is tested in a case study. The results indicate that the modeling process facilitates identification of critical factors of the PA, that the PA models capture and describe the structure, capabilities, and expansions of a PA, and that the PA models can facilitate dialogue across stakeholder groups.

Keywords: Production modeling, system modeling, production architecture, production modeling, product architecture, concurrent engineering.

1 Introduction

Architecture and platform based design has been successful in supporting concurrent engineering of products and production systems (Matt 2008; J. R. Jiao, Zhang, and Pokharel 2006), but the data on and definition of the products and the production system that existing approaches in literature rely on, are not complete in the early phases of development. To support the development of the production system despite the incomplete definition of both the products and the production system, two approaches may be valuable: (1) Modeling the incompletely defined Production Architecture (PA) as the capabilities of the production system and the deliberate organization of the functions required onto the physical elements of the products or production system, and the relations between elements (adapted from (Ulrich 1995; Andreasen, Howard, and Bruun 2014)). (2) Developing the PA concurrently with the development of the product architecture that will define the products to be produced by the PA. To accomplish this, however, tools and methods that fit to the incomplete definition of both the product architecture and the PA must be identified or developed.

Figure 1 shows a simplified system view of a production system. A typical production system is a complex system with many parameters and stakeholders to consider (Jepsen 2015). The production system transforms material inputs in the form of raw materials into finished product variants (Zelenović 1982). Its structure comprises the processing equipment, which performs functions to provide the transformation in accordance with the requirements, and it is affected by the external environment that defines the nature and constraints of the production task (Skinner 1985). The production architecture is thus derived from the production task, which determines what the production system should be particularly good at.

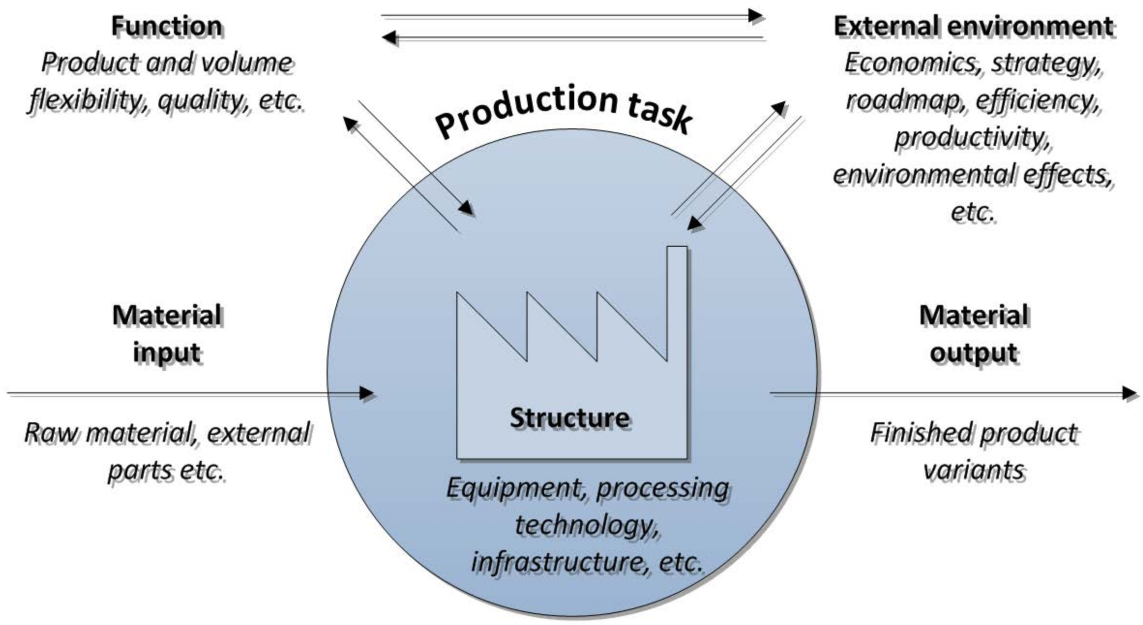


Figure 1: The production architecture is derived from the production task.

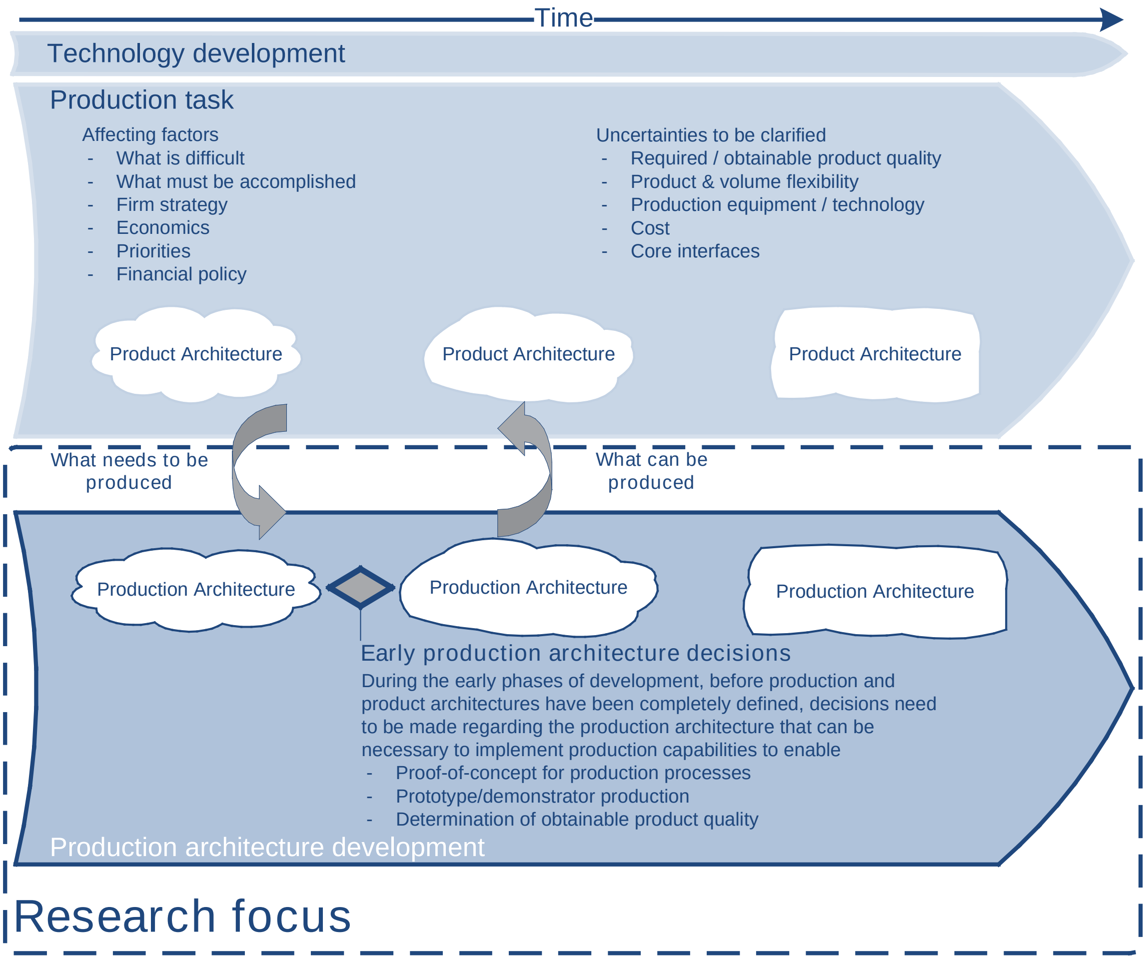


Figure 2: The definition of the production task and the production architecture is gradually made more complete during development.

The early phases of development covering Technology Readiness Levels (TRL) 1-5 are often termed technology development and fit poorly within the traditional management techniques and instead require tailored process solutions (Cooper 2006; Mankins 2009). Concurrent development of product architecture and a PA from an early phase is illustrated in Figure 2. The production task definition (Skinner 1985) in the early phases includes external factors that affect the task and the challenges of the production system and the development of the product architecture. Considerable uncertainties can be faced at the outset of the development, regarding e.g. product design (including product variants), product performance, required and obtainable product quality, production processes, and production technologies. During the development, there is a need to clarify the production task, iterating between what needs to be produced – to be able to design the right PA – and what can be produced – to be able to design the right product architecture. The design of the PA requires determination of performance criteria such as cost, required and obtainable product quality, return on investment, volume and product flexibility (Skinner 1985). At an early stage, a capability to produce prototypes may be needed and new processes must be tried and tested to determine e.g. obtainable product quality (Galagan et al. 2011). At later stages a PA ready to produce launch products that meets the required cost levels, product quality, and product and volume flexibility must be designed and implemented. Investments in pilot production facilities early in the project need greater manufacturing flexibility as there are greater uncertainties than in later stages; but as flexibility comes at a cost (Jain et al. 2013), the investments need to be based on information on the capabilities provided by the investments – both in terms of what production capabilities are provided and what challenges can be investigated by making the investments. This research focuses on modeling a PA to support PA development and investment decisions during an early phase of development.

1.1 Structure of the paper

The remainder of the paper is structured as follows. First the requirements for the model are investigated in section 1.2, by establishing what needs to be clarified during development of the PA. In section 2, existing system models and production models in literature are reviewed and compared to the requirements for an early phase PA model. In section 3, the research aim and method presents the background for the research and how it was performed. Section 4 describes the contents of the PA model and its links to relevant literature. Section 5 describes a case where the PA modelling framework was applied and section 6 presents the results from implementing the models in the case. Section 7 presents a discussion on the suggested modelling framework based on theory and findings from the case study. Section 8 presents the conclusions from this research.

1.2 Requirements for a Production Architecture model

To be able to support PA development and investment decisions in an early phase of development through modelling of the PA, a clarification of what modelling elements such a model should contain is needed by identifying relevant production system design factors. To obtain an overview of relevant factors for PA development, a literature search was performed in Google Scholar using combinations of the search terms “manufacturing”, “manufacturing system”, “production”, “production system”, “technology”, “process”, “design”, “development”, “selection”, and “architecture”. After using the titles of search results as a filter to identify potentially relevant papers, the abstracts were read to identify relevant papers. To support this identification a list of relevant factors for production system design from literature has been used as a reference (Skinner 1985). The focus within this work is on identifying factors relevant to modelling a production system under development; to identify what it is, what it can do, and what it should be able to do in the planned future.

The following is a categorized list of relevant factors that forms the requirements of what should be represented in a PA model at an early phase:

1.2.1 Structural elements of a PA (what is it?)

- The constituent elements, such as sub-systems, the equipment and workstations (Matt 2008), and functions and structure, where the structure is the organization of the physical elements and their relations (Hubka and Eder 1988).
- Links from a production system’s elements and functions to elements of the product architecture through dispositional effects (Olesen 1992).
- Indication of the choice of production technology, as it is a key determinant in the achievable functionality of the production system and capital expenses required to implement the production system (Skinner 1985; Farooq and O’Brien 2012).

1.2.2 Functional elements of a PA (what can it do?)

- Product flexibility, as it is the capability to produce new product variants economically (Jain et al. 2013), which is necessary when the product architecture description is not complete, although more flexibility is not necessarily better – the aim should be to obtain the right flexibility (Matta et al. 2010; Boyle, Kumar, and Kumar 2002).
- Volume flexibility, as it is the range of production volume within which the production system can profitably produce products and is especially important in new product introduction (Negahban, Yilmaz, and Nall 2014)
- Processing and setup times, batch sizes, and the amount of partially produced goods within the production system, as these greatly affect the performance of the production system (Matt 2008; Suh, Cochran, and Lima 1998; Russell and Taylor III 2011).
- Product differentiation points, as these affect product design as well as product and volume flexibility (Yang and Burns 2003)
- Indication of obtainable quality, as quality is generally prioritized over flexibility and should be considered during production system development (Inman et al. 2013).

1.2.3 Expansions to the PA (what should it be able to do in the future?)

- Production volume scaling, as moving from a laboratory setting to industrial production scale can require rigorous experiments on industrial production equipment to identify performance parameters and improve obtainable quality (Galagan et al. 2011; Taguchi, Chowdhury, and Wu 2004).
- Capabilities, as these can be expanded upon to enable delayed investment for capabilities that are not needed until later on – interfaces between sub-systems are central to facilitating capability expansion (Jain et al. 2013).

Some of the most critical elements of the production system are the required and obtainable product quality, return on investment, flexibility for volume and product changes, cost and productivity (Skinner 1985). As a PA can be assumed to be incompletely defined during an early phase, a complete model of all these elements may not be achievable or prudent – while e.g. process technology and scaling principles will be highly relevant in the early phases, batch sizes and setup times are of greater relevance in later phases and it may only be relevant to investigate scaling of critical processing equipment.

2 Literature review

The modeling of a PA at an early phase can be seen as a model of three facets of the PA: Its structure – to identify processes, critical equipment, and process flow; its capabilities – to determine what the PA is capable of producing; and its expansions – to identify planned and implemented improvements to the PA's capabilities.

2.1 Modelling the structure of the PA

System modelling has been applied to model the structure of systems as comprising functions and structure, where the structure is the organization of the physical elements and their relations (Hubka and Eder 1988). Production systems can be seen as and modelled as large systems (Hvam 2006; Suh 1995). In production modelling, the constitutive modelling elements are the individual processing equipment and workstations (Suh 1995). The relations between structural elements in the production system primarily take the form of material and tool handling.

Flow models are a common way of modelling the structure of a production system and show the processes of the production system and routing or flow between processes (Meyer, Creux, and Weber Marin 2006). The detail in process flow models varies, from illustrating only the flow between processes to more detailed models identifying product variant creation, utilizing standardized graphic notations, IDEF or UML modelling formalisms, and links to process simulations and routing optimization algorithms (Perera and Liyanage 2000; Oscarsson and Moris 2002; Silla 2003; Zhang 2007; Mortensen et al. 2011).

Layout models are primarily used to determine an optimal layout of production equipment within the production facilities (Russell and Taylor III 2011; De Carlo et al. 2013). They can span entire factories or be focused on a single workstation (Jepsen 2015). Layout models are focused on the physical layout and relations between equipment.

2.2 Modelling the capabilities of the PA

Few models depict the capabilities of a production system directly. Some variants of flow models include details such as the product variant differentiation points, which provides an indication of what product variants can be produced by the production system (Mortensen et al. 2011). Layout models may also contain information on capabilities, such as capacity, process, and cycle time (Jepsen 2015). Value Stream Maps (VSM) can be seen as depicting capabilities of the whole value chain, mostly in the form of performance parameters (e.g. processing and cycle times) and may contain similar capability information as layout models (Lasa, Laburu, and Vila 2008; Rother and Shook 1999).

Capability modelling can be done using graphical elements such as illustrations of Work in Progress (WIP) variants at differentiation points and bar graphs for ‘production volume capacity (Mortensen et al. 2011) or as numerical data on performance parameters (Jepsen 2015; Braglia, Carmignani, and Zammori 2006).

Linking the products to the PA may be viewed as a form of capability modelling and has been done using linked models for Bill-of-Materials and for product and process platforms (J. Jiao et al. 2000; J. R. Jiao, Zhang, and Pokharel 2006). These links are utilized in the production process planning approach, but as they are based on optimization using extensive historical data on products and processes (Zhang and Jiao 2013), this approach is not fit for direct implementation at an early phase. An integrated model can be used to model the production system with the WIP as an integrated part of the model, but this requires multiple models to model the different states of manufacture and the detailed interactions between the parts and the production equipment (Gedell, Michaelis, and Johannesson 2011).

2.3 Modelling expansions to the PA

In literature, quantitative models compare production technologies on a cost basis with regards to demand and capacity (Fine and Freund 1990), include flexibility and uncertainty (Bihlmaier, Koberstein, and Obst 2009) and consider the optimal choice of production technology based on investments, costs, capacity capabilities and demand (Li and Tirupati 1994). But these quantitative approaches require input data in the form of demand and cost estimates and lack focus on modelling the constitutive aspect of expansions – how expansions affect not only capabilities but also structural aspects of the expansion plans. The expansions to a PA can include multiple layout diagrams to show alternative configurations of a workstation, including performance data on each alternative (Jepsen 2015), which enables modelling of both structural and capability expansions using multiple uniform models. A multiple model approach is also used with VSM's, where two maps are generally generated; one for the current state and one for the future, improved, state (Rother and Shook 1999).

2.4 Summary of literature review

There exist in literature a variety of approaches to modelling the production system from a diverse set of perspectives. Structural models facilitate determination and communication of the structure of the production system, but generally lack information on capabilities and expansions. Existing models that include capabilities are focused primarily on mature production systems producing well-defined product families. While many capabilities of the production system are modelled in existing models, the modelling is either limited to a few performance parameters or rely on extensive data sets on products and processes to support optimization of the production system. Lacking numerical data sets, quantitative expansion modelling is deemed unfit at an early phase, while modelling expansions to the production system through the use of multiple models showing the differences between 'current' and 'future' states have been successfully applied in industry. However, models have not been found that combine a model of the structure and capabilities of the production system with expansions modelling at an early phase of development.

3 Research aim and method

In this section the Research aim and Research method are presented, i.e. the "why" and "how" of the research.

3.1 Research aim

This research focuses on developing a modelling framework that captures and facilitates communication of critical PA parameters during the early phases of concurrent product and production development. In light of uncertainties regarding both the product and process architectures in the early phases, the framework must facilitate a gradual clarification of critical PA parameters as development progresses.

The aim is both to develop and test a modelling framework that supports firms in identifying critical production system development parameters and decisions in the early phases of development; a framework with a solid theoretical foundation and fit for use within an environment where not much is known at the outset and what is believed to be true may change rapidly during the development process. To support clarification of parameters across stakeholder groups during the development, the framework should fit multiple audiences and present a framework within which critical parameters can be identified.

3.2 Research method

The research method will be discussed with regards to two subjects: the development of the modelling framework and the testing of the modelling framework.

3.2.1 Development of modelling framework

The modelling framework was developed on the basis of literature, experience, and feedback from practitioners. The literature foundation was formed by a literature review of theories on systems theories, integrated product development, production system design, production modelling, manufacturing flexibility, process platforms, product architectures, and product family development. The researchers drew on experience from research within product family development, production modelling within product development, and integrated product development from the research group with a background in mechanical engineering and operations management. Industrial practitioners provided feedback through testing, as well as providing ideas based on best practices and information on requirements for the modelling framework.

A framework for modelling a PA from the early phases of concurrent development in support of identifying critical parameters and decisions on the PA was developed on the foundation described above. The modelling framework supports identifying parameters and decisions by framing the contents of the PA model on the basis of literature on production systems and product architectures and the interfaces between these: what is needed by the product architecture and what the PA can provide. The resulting model describes what the PA is (its structure and production technologies), what it can do (its functions and capabilities), and how it can or will be expanded. The modelling framework focuses on describing the PA for production systems with a product layout (Russell and Taylor III 2011), where the sequence of operations for a product dictate the layout (e.g. an assembly line). Information gathered through interviews and workshops with experts is organized in a visual model of the envisioned PA that facilitates communication of identified parameters and decisions to heterogeneous stakeholder groups from an early stage of development.

3.2.2 Testing the modelling framework

The modelling framework was tested in an industrial setting to evaluate whether it would be practical to use within its intended setting, whether critical parameters and decisions would be identified through use of the modelling framework, and whether communication of the aforementioned parameters and decisions to heterogeneous stakeholder groups would be facilitated through the application of the modelling framework. The test was meant to provide empirical data on the applicability of the framework in the early phases of a concurrent development project.

The researchers collaborated with the production manager responsible for the production development to model the production system and its planned expansions and development tasks. The researchers' role was to perform the modelling task with input from interviews and workshops with practitioners, along with existing documents describing the production system. Feedback was received from interviews with multiple stakeholders and direct observation was used to evaluate the use of the resulting models.

4 A framework for modelling the Production Architecture

The modelling elements of the PA modelling framework, illustrated in a generic format in Figure 3, provide information on the PA from the three distinct perspectives. The *structure* of the PA describes what it is by modelling two levels; (1) main stations, processes, flows, parts, and tools, and (2) critical equipment and the definition of product characteristics. The *capabilities* of the PA describe what it can do through modelling the product variants produced, the product flexibility, volume flexibility for each main station. The *expansion* plans describe changes to the structure and capabilities of the PA that are expected to be realized through investments or other decisions made during the development of the PA. These three perspectives stem from themes identified in the literature search on requirements for a PA model, on which the modelling framework is based, along with literature covered in the literature review.

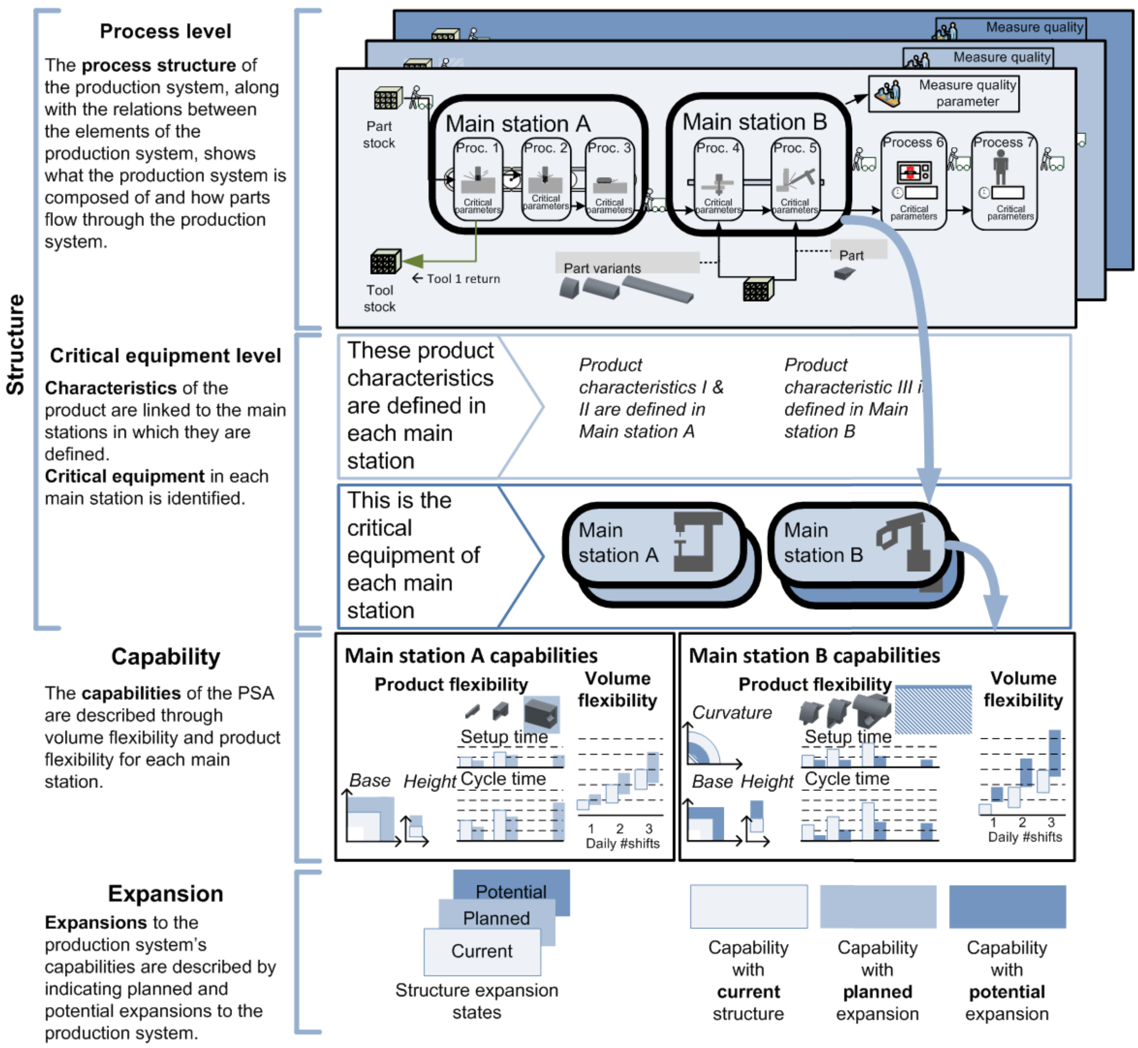


Figure 3: A PA model includes structure, capability, and expansion dimensions to support early PA decisions.

4.1.1 Structure

The structure of the PA is modelled at two levels – a process level and an equipment level – to describe the structure of the PA, the production technology choices made, and the dispositional effects between the PA and the product architecture. The processes are modelled on the basis of function modelling and the Generic Production Flow (Ulrich 1995; Mortensen et al. 2011) to describe the processes in the PA and the relations between them in the form of interfaces. The equipment level describes critical equipment and workstations and the critical product characteristics that are defined at each of them.

The process level includes individual processes, groups of interlinked processes modelled as main stations, stock, and material handling. Each process is described with a symbol and a note of critical process parameters that are central to increasing the capabilities of the PA or determining obtainable product quality. The interfaces between processes describe the flow of parts, work pieces, and tools.

The equipment level description emphasizes the dispositional relationship between the PA and the product architecture (Olesen 1992). To achieve changes in product characteristics, the equipment linked to the definition of the particular product characteristics may need to be updated or changed – and changes to the equipment may have an effect on the product characteristics linked to the equipment.

4.1.2 Capability

The capabilities of the PA represent functional aspects. They are modelled with an emphasis on product variant creation and system level manufacturing flexibility, which includes process, routing, product and volume flexibilities (Sethi and Sethi 1990). Flexibility is modelled to indicate what can be handled by the PA and what its limitations are, while the product variant creation indicates product differentiation points (Yang and Burns 2003) and relates the PA to the currently known spectrum of achievable product variants.

Process flexibility enables the production of multiple product variants using the same equipment, enabling higher utilization of machines and the ability to react to changes in market demand between product variants (Jain et al. 2013). In the resulting PA model it is communicated by modelling the part-related parameter ranges available in the main stations and by illustrating the known set of relevant part types that can be produced. Tools and parts are noted to provide information on what needs to be changed to achieve new product variants.

Routing flexibility supports load balancing activities by providing scheduling leeway in the form of alternative routing sequences – depending on the product mix to be produced (Sethi and Sethi 1990) – and can be illustrated through alternative or optional interfaces using dotted lines in the model.

Product flexibility defines how quickly the firm can deliver new product variants (Sanchez 1995); identified product related dimensions, geometries, and relevant material parameters that can be handled by the PA are modelled to allow identification of product variants that can be produced without further capital investment in the production system. As in the GPF, product differentiation points are modelled to identify the flow for each product variant and the number of product variants that must be handled at each step in the production system (Mortensen et al. 2011).

Volume flexibilities define the firm's ability to produce varying quantities of its products profitably. By modelling the production volume ranges within which the firm's production can remain profitable, the volume flexibilities of the production system, which are particularly important in the growth phases of products or product portfolios (Negahban, Yilmaz, and Nall 2014), are identified.

4.1.3 Expansion

One of the requirements for a PA model is to deal with the future perspectives of the PA, including how scaling of the PA will be implemented. PA investment decisions during development are necessary to increase the capabilities of the PA, whether they are dealing with how to increase capabilities during development or how to ramp up capabilities to prepare for product launch. These changes to the capabilities are the result of changes to the equipment or structure of the PA and can fall into two categories: Planned expansions for which implementation is to be initiated and potential expansions that are defined but will be implemented at a later stage. Potential expansions carry greater uncertainty. The Generic Production Flow (GPF) (Mortensen et al. 2011) includes planned volume expansions in the model, but the planned and potential changes to the PA are modelled either as part of a single model or as a separate model, similar to current and future state Value Stream Maps (VSM) (Braglia, Carmignani, and Zammori 2006). Each change in the structure or capabilities is colour coded to emphasize both what the changes comprise and their effect on the PA's capabilities.

5 Case study

The modelling framework was applied within a large technology development project aimed at commercializing transducers based on Electro-Active Polymer (EAP) technology (Guðlaugsson et al. 2014). Within the project, concurrent development was performed on the base material, production of the EAP-film and transducers, transducer design, high-voltage electronics design, and technology prototypes utilizing the EAP-transducers. The project involved both investments in and development of equipment and processes for the production of EAP-film and transducers within an uncertain environment. As the technology and products were being developed concurrently, specifications, capacity requirements, quality factors, and the supply chain design, were constantly changing and being identified along the way. In the face of uncertainties, decisions needed to be made on the design of the production system based on what it would enable in terms of production of EAP-products and communicated to a heterogeneous group of collaborating stakeholders to ensure that the production system being developed fits the production of the EAP-film and transducers.

The case covers the production of EAP film, a corrugated silicone film sandwiched between metal electrodes deposited onto the film, in various potential configurations (Kiil and Benslimane 2009). The PA comprised six main stations, twenty-eight individual processes, and two main flow paths. The number of explicitly stated film variants was twelve, but in addition to this number, thickness and width of the film could be varied in product configuration.

5.1 Modelling process

Three PA models were created, one for the state before the project started, one showing the plans being implemented at the time of the modelling activity, and one showing the potential expansions within the project (shown in Figure 4). The three models were presented on a single large poster that also contained capacity increase estimates and information related to project tasks (Ravn, Guðlaugsson, and Mortensen 2014). Cycle times for individual product variants and setup times were not included in the models, as these were seen as secondary information in the ramp-up project.

The case models were created during a period of one month, which included two workshops with the participation of, on behalf of the case firm, the production manager, process engineers, and the project manager. Data collection for the modelling task also consisted of a walkthrough of the production facilities, photographing and note-taking, and review of existing, outdated, production flow charts. The models were populated and updated between the workshops and feedback was received on the drafts for refinement of the models and the modelling framework.

The models were implemented as standalone graphical documents in Microsoft® Visio® and 3D illustrations were created in PTC® CREO® Parametric 1.0. Process icons were purpose-made for the EAP film PA models. The electronic versions were exclusively used for modelling purposes. For all discussions and workshops, large format paper printouts were used.

5.2 Production Architecture models

The PA models, shown in Figure 4, focused on the structure, capabilities and expansion of the EAP-film PA.

5.2.1 Structure

The models showed the elements of the PA and their relations: the main stations, critical processes, tools, storage and transport of material, and quality control (QC) stations. Each process included the primary process parameters that were related to achieving the desired film quality. The main stations were central production equipment or process groups and they identified the chosen production technologies for each PA instance; in the case of the future state PA model these were material mixing processes, a film coating machine, a de-lamination and lamination station, a metal deposit machine, a pre-conditioning station, and a film coating tool cleaning machine.

The equipment level linked the main stations to the product characteristics of the EAP film, i.e. breakdown voltage, film width, and lamination configuration. This identified where the production technologies and equipment affect the obtainable quality of the resulting products.

5.2.2 Capabilities

Product flexibility of the main stations was indicated as the available range in major film parameters: film thickness, width, length, and corrugation pattern. Volume flexibility was only indicated as the maximum capabilities as the production task was focused on prototype production and demonstration of production volume scalability. The cycle times for a standardized film roll of a certain length, width, and thickness at the outset of the project were noted for each main station in the PA model of the production system, and as relative improvements in the current and future state PA models.

Illustrations of basic film configurations indicated product variant differentiation points, while more variants were possible through dimensional differentiation, such as thickness, length, or width variations – these capabilities were noted as performance ranges.

5.2.3 Expansion

Intended and implemented scaling of capabilities were noted as the improvements from the PA at the start of the project. These changes included new equipment, flow path changes, product variant production capabilities, dimensional capabilities, and production capacity capabilities. Updated main stations were indicated by a green border. The production capacity expansions were noted as relative output increases, in comparison to the PA before the project.

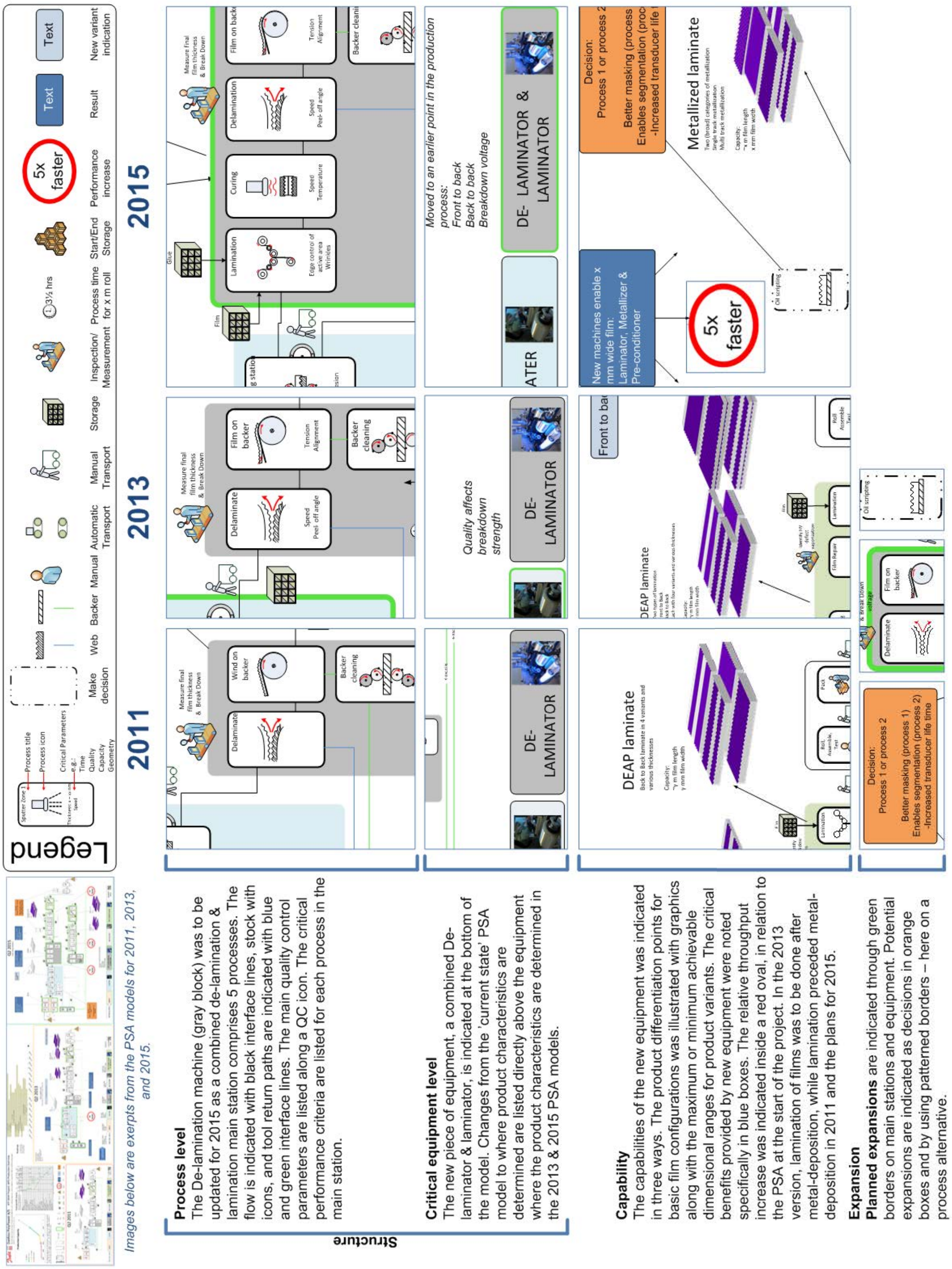


Figure 4: The PA models supported identification of the structure, capability and planned expansions of the PA.

6 Results from case

The modelling approach was considered successful by the industry participants. The process was praised for being effective in capturing the information in the models, including the use of workshop iterations with draft posters to facilitate discussions on the models' contents.

The models captured the structure of the PA in development which included critical parameters and dispositional links to the product architecture, as well as equipment, quality control points, and production technologies. Decisions to be made regarding investments in new equipment critical to the production process were identified and communicated. Lastly, the models depicted the capabilities of the PA within product flexibility, volume flexibility, and parameters affecting obtainable product quality before and after implementation of implemented and intended expansions aimed at scaling the capabilities of the PA.

The modelling process itself facilitated discussions within the production development team on the production flow and the parameters involved across processes which were described as being clearer across the team than before. An example of this was a discussion on obtainable laminate thickness, which relates to material properties after mixing, presence of foreign particles in material or coating web, the coating equipment, imperfections in coating web (mould for corrugation pattern), adhesion to coating web, peel-off angle in de-laminator, and process control in metal deposit machine. The sheer number of elements of the PA and parameters involved made the overview provided by the PA models valued by the participants in the discussions.

There were three mechanisms that could be identified as facilitating elements in the modelling process: (1) The identification of critical parameters for models made tacit knowledge explicit through internal discussions in the production development team on what parameters were critical in achieving improved product quality. (2) The link between processes and critical parameters on one hand and product characteristics on the other were valuable for discussions inside and outside the production development team. (3) By aiming at clearly identifying the expected benefits of planned expansions, the production development team was forced to explicitly discuss why the expansions were being considered and what benefits were expected to be realized by implementing the expansions.

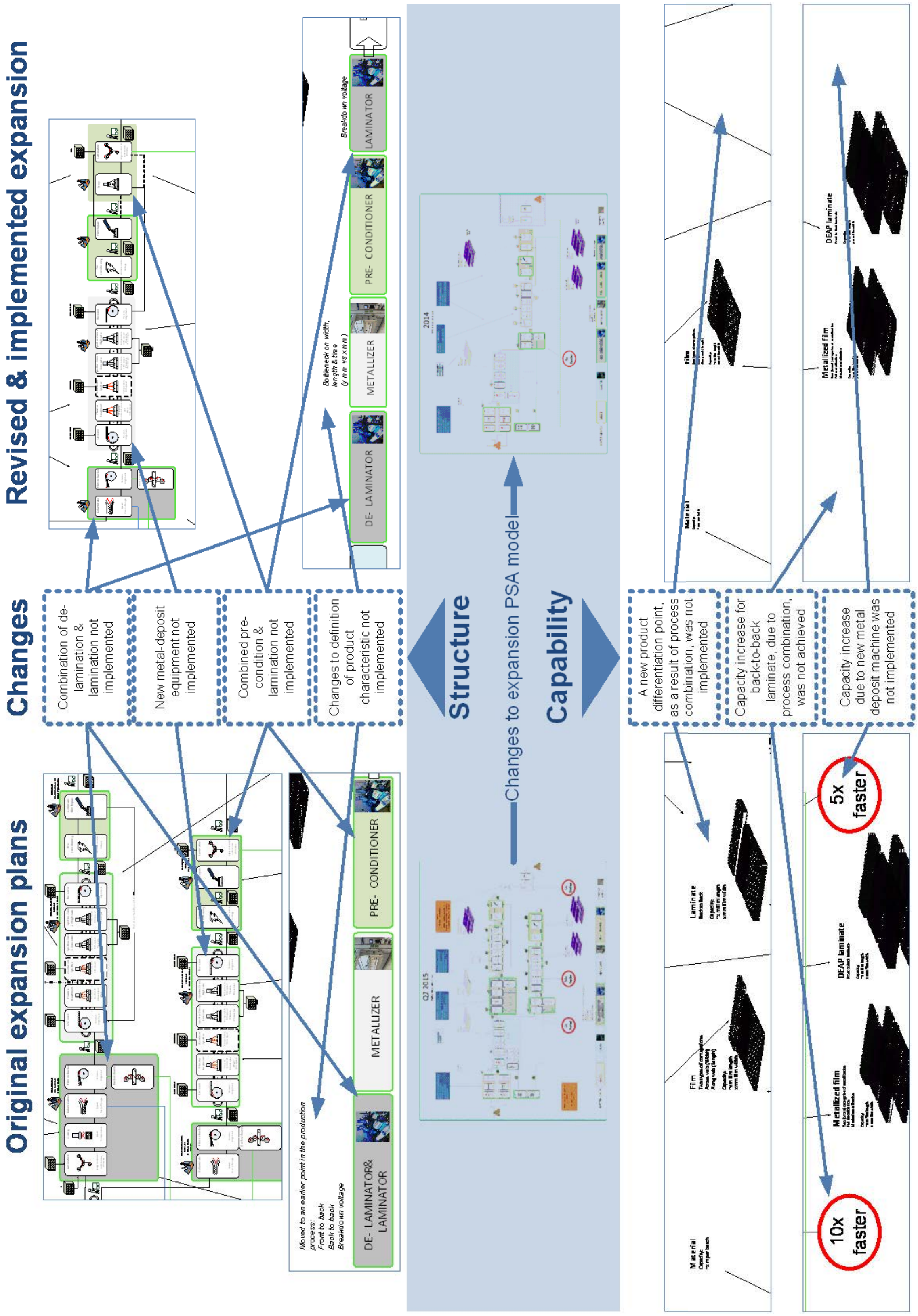


Figure 5: The effects of decisions can be seen in the updates to the PA model showing potential expansions.

The resulting PA models were used to communicate the intended expansions to the PA and their expected benefits to decision makers. The models were judged to be valuable for decision makers to assess the cost-benefit ratio of expansion investments. Some of the planned expansions were not implemented – such as updating the metal deposit machine and adding oil masking – as the benefits were not deemed to warrant the investment at that time. A planned expansion of a machine capable of combining de-lamination and lamination processes was not successful, which affected the capabilities achievable in the project. The consequences of these decisions and failed development were modelled in a later iteration of the PA model of the potential expansions as shown in Figure 5.

The PA models also supported communication of the PA to other stakeholders in the project, for whom an understanding of the PA was valuable for their own work, such as material developers and product developers.

While the PA models were generally well received, the models contained details that were irrelevant for some recipient groups who had to disregard the irrelevant information. Another criticism on the modelling approach was that for many tasks in the daily work on individual processes, the models were too comprehensive and so simpler flow charts or block diagrams with little explicit information were often used instead.

7 Discussion

In order to assess the appropriateness of the proposed modeling framework, the contents of the resulting models are evaluated against the required contents listed in the introduction and how this research contributes to the literature referred. The findings from the case study are included in this assessment.

The requirement of describing the structure of the PA – its sub-systems, equipment, production technologies, and their relations (Matt 2008; Hubka and Eder 1988; Skinner 1985) – is fulfilled to a point where the models can be applied to the needs at the early stage of development. The physical elements and their functional relations can be identified, while their physical structure and the PA layout are omitted as the main focus at that stage was on proving the ability to produce products and investigate obtainable quality; the scale required for commercial production volumes – where layout design is important – was not being reached at that point. The focus on quality at that stage also emphasizes the importance of identifying dispositional links to the product architecture (Olesen 1992) and both quality parameters (Taguchi, Chowdhury, and Wu 2004) and incorporation of quality control points (Inman et al. 2013).

The proposed models include capability descriptions fulfilling the requirements; product and volume flexibility (Matta et al. 2010; Boyle, Kumar, and Kumar 2002; Negahban, Yilmaz, and Nall 2014), processing times, setup times, indications of partially produced goods (Matt 2008; Suh, Cochran, and Lima 1998; Russell and Taylor III 2011), product differentiation points (Yang and Burns 2003), and indications of quality (Inman et al. 2013). The case study, however, is limited in this regard, but the limitations were deliberate and in accordance with the purpose of the model in the case – which corresponds to a pragmatic approach to modeling (Lindemann 2014). In the situation in the case study, cost and economical production volume were of limited interest in comparison to obtainable product quality, fitting capabilities within product flexibility, and demonstrating that production volume could be scaled up. Batch sizes and processing times were included to communicate the scaling of production volume, an important step for scaling up to industrial production volumes (Galagan et al. 2011;

Taguchi, Chowdhury, and Wu 2004) but setup times and partially produced goods were omitted to reduce the amount of information in the models.

The expansion modeling in the case study was limited to the planned expansions within the project. Potential expansions were not implemented as obtaining the capability expansions they would have provided were not needed until later on. While investments in capabilities can be delayed until needed (Jain et al. 2013), uncertainties about whether the investments would provide the right capabilities later in development mean that other investments could replace the modeled expansions.

Testing the modeling framework in industry provided a preliminary validation of the approach in the following dimensions: whether it was practical to use, whether critical parameters and decisions would be identified through use of the modeling framework, and whether communication of these parameters and decisions would be facilitated through the application of the modeling framework.

The time frame available for constructing a model is an important aspect of its practicality (Lindemann 2014). The application of the modeling framework in industry showed that within a short time period, the PA models could be constructed using a well known software package using limited resources.

One of the central results from the application of the framework was that the modeling process forced the production development team to discuss and contemplate the production processes in plenum at a more detailed level and more holistically than was being done before. Now, the possibility that discussions at these levels would have occurred without application of the modeling framework cannot be excluded. However, statements from the participants that identify the modeling process as the catalyst for the discussions and previous findings on the use of models in design (Bergman, Lyytinen, and Mark 2007; Henderson 1991) support the notion that the modeling process facilitated the identification of the critical parameters and negotiation of the final contents of the PA models.

Decisions can be said to be modeled in two ways in the models. The explicit modeling of decisions yet to be made by the production development team and the implicit modeling of decisions made by the production development team, modeled as planned expansions. The decision not to invest in new metal deposition equipment is an example of the latter. System models support decision making through modeling the consequences of decisions that are most relevant to the aims of the development task (Maier et al. 2014). While the modeled decisions represent only a subset of all decisions made regarding the PA during development, there is consensus amongst the participants that the modeling framework captured the critical decisions that required broader stakeholder consideration and the consequences of the decisions.

Observations of the use of the PA models in plenary sessions during a project symposium and feedback from participants regarding other uses of the models indicate that the PA models are valuable as communication support tools, which is in line with existing literature on the use of models in development (Alabastro et al. 1995; Bruun, Mortensen, and Harlou 2014). Observations of the PA models being a focal point of dialogue between heterogeneous stakeholders support previous results on the value of architecture models and graphical descriptions as means to facilitate communication between heterogeneous stakeholders (Jepsen 2015; Henderson 1991). System models have been described as a means to explore and understand a simplified version of the complex relationships between a system's properties and characteristics (Albers and Wintergerst 2014). The common, simplified perspective provided by the PA models provided stakeholders outside the production development team with the means to explore and understand the PA – a foundation for discussing the PAs critical parameters and decisions.

The research is limited in that the modeling framework has only been applied in one project. Therefore, it can be debated whether these results can be carried onto other projects and other firms. However, while any case can be considered unique, there are elements in the industrial project that can be of relevance for other firms and other industries. The main focus of the framework is modeling the production architecture at an early phase to support investment decisions – with uncertainties regarding product and production architectures. Technology development occurs in conjunction with product and production development in other industries, where these circumstances also arise (Walsh 2004). The development of production processes to increase obtainable product quality and production capacity is also described in literature involving other firms (Galagan et al. 2011). Furthermore, the modeling framework is founded on theoretical literature on systems and production modeling, production system design, and production flexibility. Therefore, it is likely that there are other firms in industry that could benefit from applying this modeling framework.

8 Conclusion

In the early phases of product development, before the products have been fully defined, it can be necessary to invest in production equipment to obtain production capabilities to e.g. determine obtainable product quality on industrial production equipment, produce prototypes, and develop production processes. To obtain suitable production capabilities, it must be identified what constitutes fitting capabilities, what elements of a production system must be taken into account, and a decision must be made on which production capabilities shall be acquired and how. The structure of the production system must be identified, the capabilities of a production system with that structure must be determined, and the expansion of the capabilities through the development of the production system should be decided upon. A modeling framework, aimed at supporting the development of a Production Architecture concurrently with development of a product architecture from an early phase, the Production Architecture (PA) modeling framework, is proposed. The modeling framework builds upon and combines elements from existing literature to capture and present the structure, capabilities and expansions of a PA during development. The contribution of this work lies in modeling the combination of structure, capabilities, and expansions.

A case study presents the implementation of the modeling approach in industry within an early phase of a concurrent product and production development project. Results from the case study indicate that (1) the modeling process facilitates identification of critical information on the PA; (2) the framework captures and presents implicit and explicit decisions made, or to be made, by the production development team; (3) the resulting models facilitated dialogue by acting as boundary objects between heterogeneous stakeholder groups and by confronting recipients with a concrete perspective on the PA and its capabilities; (4) the framework is suitable for implementation in a dynamic, uncertain, environment at an early phase of development.

The validity of the framework is argued to lie in two factors: its theoretical foundation and its implementation in a case study in industry. The implementation in an industrial case within the intended environment where decisions were made within a heterogeneous group of stakeholders was considered valuable. As the framework is developed on the basis of a broad theoretical foundation and literature has examples of cases where product and production development is performed concurrently from an early phase, it is likely that it can be transferred onto other, similar, environments.

Further research includes further testing iterations to refine the framework. This includes implementing the modeling approach in more projects to test all elements of the modeling framework. A particularly valuable test would be to implement the framework in a project where it could be followed from the early phases through to commercialization or handover to mature new product development processes. Identifying how the framework can interface with more mature development processes would be valuable to identify other potential research directions for the PA modeling framework.

Acknowledgements

The authors want to thank Innovation Fund Denmark for the financial support and the collaborating partners for their role in supporting this research.

9 References

Alabastro, MS, Gerd Beckmann, Gina Gifford, Anne P. Massey, and William A. Wallace. 1995. “The Use of Visual Modeling in Designing a Manufacturing Process for Advanced Composite Structures.” *IEEE Transactions on Engineering Management* 42 (3): 233–42.

Albers, Albert, and Eike Wintergerst. 2014. “The Contact and Channel Approach (C&C2-A): Relating a System’s Physical Structure to Its Functionality.” In *An Anthology of Theories and Models of Design: Philosophy, Approaches and Empirical Explorations*, edited by Amaresh Chakrabarti and Lucienne T M Blessing, 151–71. London: Springer London.

Andreasen, Mogens Myrup, Thomas J Howard, and Hans Peter Lomholt Bruun. 2014. “Domain Theory, Its Models and Concepts.” In *An Anthology of Theories and Models of Design*, edited by Amaresh Chakrabarti and Lucienne T. M. Blessing, 173–95. London: Springer London.

Bergman, Mark, Kalle Lyytinen, and Gloria Mark. 2007. “Boundary Objects in Design: An Ecological View of Design Artifacts.” *Journal of the Association for Information Systems* 8 (11): 546–68.

Bihlmaier, Ralf, Achim Koberstein, and René Obst. 2009. “Modeling and Optimizing of Strategic and Tactical Production Planning in the Automotive Industry under Uncertainty.” *OR Spectrum* 31 (2): 311–36.

Boyle, Todd, Vinod Kumar, and Uma Kumar. 2002. “The Implementation of Manufacturing Flexibility: A Conceptual Framework.” In *Proceedings of the Annual Conference of the Administrative Sciences Association of Canada Production and Operations Management Division*, edited by Ozhand Ganjavi, 23:52–61. Winnipeg, Manitoba: I.H. Asper School of Business, The University of Manitoba.

Braglia, M., G. Carmignani, and F. Zammori. 2006. "A New Value Stream Mapping Approach for Complex Production Systems." *International Journal of Production Research* 44 (18-19): 3929–52.

Bruun, Hans Peter Lomholt, Niels Henrik Mortensen, and Ulf Harlou. 2014. "Interface Diagram: Design Tool for Supporting the Development of Modularity in Complex Product Systems." *Concurrent Engineering* 22 (1): 62–76.

Cooper, Robert G. 2006. "MANAGING TECHNOLOGY DEVELOPMENT PROJECTS." *Research Technology Management* 49 (6): 23–31.

De Carlo, Filippo, Maria Antonietta, Orlando Borgia, and Mario Tucci. 2013. "Layout Design for a Low Capacity Manufacturing Line: A Case Study." *International Journal of Engineering Business Management* 5 (35): 1–10.

Farooq, Sami, and Chris O'Brien. 2012. "A Technology Selection Framework for Integrating Manufacturing within a Supply Chain." *International Journal of Production Research* 50 (11): 2987–3010.

Fine, C. H., and R. M. Freund. 1990. "Optimal Investment in Product-Flexible Manufacturing Capacity." *Management Science* 36 (4): 449–66.

Galagan, Yulia, Ike G. de Vries, Arjan P. Langen, Ronn Andriessen, Wiljan J H Verhees, Sjoerd C. Veenstra, and Jan M. Kroon. 2011. "Technology Development for Roll-to-Roll Production of Organic Photovoltaics." *Chemical Engineering and Processing: Process Intensification* 50 (5-6). Elsevier B.V.: 454–61.

Gedell, S., M. T. Michaelis, and H. Johannesson. 2011. "Integrated Model for Co-Development of Products and Production Systems - A Systems Theory Approach." *Concurrent Engineering* 19 (2): 139–56.

Guðlaugsson, Tómas Vignir, Poul Martin Ravn, Niels Henrik Mortensen, and Rahimullah Sarban. 2014. "Front-End Conceptual Platform Modeling." *Concurrent Engineering* 22 (4): 267–76.

Henderson, K. 1991. "Flexible Sketches and Inflexible Data Bases: Visual Communication, Conscription Devices, and Boundary Objects in Design Engineering." *Science, Technology & Human Values* 16 (4): 448–73.

Hubka, V, and W E Eder. 1988. *Theory of Technical Systems - A Total Concept Theory for Engineering Design*. Berlin: Springer-Verlag.

Hvam, Lars. 2006. "Mass Customization of Process Plants." *International Journal of Mass Customisation* 1 (4): 445–62.

Inman, Robert R., Dennis E. Blumenfeld, Ningjian Huang, Jingshan Li, and Jing Li. 2013. "Survey of Recent Advances on the Interface between Production System Design and Quality." *IIE Transactions* 45 (6). Taylor & Francis Group: 557–74.

Jain, Ajai, P.K. Jain, Felix T.S. Chan, and Shailendra Singh. 2013. “A Review on Manufacturing Flexibility.” *International Journal of Production Research* 51 (19). Routledge: 5946–70.

Jepsen, Allan Dam. 2015. “Architecture Descriptions- A Contribution to Modeling of Production System Architecture.” PhD diss., Technical University of Denmark.

Jiao, Jianxin Roger, Lianfeng Zhang, and Shaligram Pokharel. 2006. “Process Platform and Production Configuration for Product Families.” In *Product Platform and Product Family Design*, edited by Timothy W. Simpson, Zahed Siddique, and Jianxin (Roger) Jiao.

Jiao, Jianxin, Mitchell M Tseng, Qinhai Ma, and Yi Zou. 2000. “Generic Bill-of-Materials-and-Operations for High-Variety Production Management.” *Concurrent Engineering* 8 (4): 297–321.

Kiil, Hans-Erik, and Mohamed Benslimane. 2009. “Scalable Industrial Manufacturing of DEAP.” In *SPIE Smart Structures and Materials + Nondestructive Evaluation and Health Monitoring*, edited by Yoseph Bar-Cohen and Thomas Wallmersperger, 72870R – 1–10. International Society for Optics and Photonics.

Lasa, Ibon Serrano, Carlos Ochoa Laburu, and Rodolfo De Castro Vila. 2008. “An Evaluation of the Value Stream Mapping Tool.” *Business Process Management Journal* 14 (1): 39–52.

Li, Shanling, and Devanath Tirupati. 1994. “Dynamic Capacity Expansion Problem with Multiple Products: Technology Selection and Timing of Capacity Additions.” *Operations Research*.

Lindemann, Udo. 2014. “Models of Design.” In *An Anthology of Theories and Models of Design: Philosophy, Approaches and Empirical Explorations*, edited by Amaresh Chakrabarti and Lucienne T M Blessing, 121–32. London: Springer London.

Maier, Anja M, David C Wynn, Thomas J Howard, and Mogens Myrup Andreasen. 2014. “Perceiving Design as Modelling: A Cybernetic Systems Perspective.” In *An Anthology of Theories and Models of Design*, edited by Amaresh Chakrabarti and Lucienne T. M. Blessing, 133–49. London: Springer London.

Mankins, John C. 2009. “Technology Readiness Assessments: A Retrospective.” *Acta Astronautica* 65 (9-10). Elsevier: 1216–23.

Matt, D.T. 2008. “Template Based Production System Design.” *Journal of Manufacturing Technology Management* 19 (7): 783–97.

Matta, A., T. Tolio, F. Karaesmen, and Y. Dallery. 2010. “A New System Architecture Compared with Conventional Production System Architectures.” *International Journal of Production Research* 38 (17): 4159–69.

Meyer, Urs S., Simone E. Creux, and Andrea K. Weber Marin. 2006. *Process Oriented Analysis: Design and Optimization of Industrial Production Systems*. *Design and Optimization of Industrial Production Systems*. Boca Raton, Fl: CRC Press.

Mortensen, Niels Henrik, Christian L Hansen, Lars Hvam, and Mogens Myrup Andreasen. 2011. “Proactive Modeling of Market, Product and Production Architectures.” In *DS 68-4: Proceedings of the 18th International Conference on Engineering Design (ICED 11), Impacting Society through Engineering Design, Vol. 4: Product and Systems Design*, edited by S.J. Culley, B.J. Hicks, T.C. McAloone, T.J. Howard, and U. Lindemann, 133–44. Kgs. Lyngby: The Design Society.

Negahban, a., L. Yilmaz, and T. Nall. 2014. “Managing Production Level in New Product Diffusion: An Agent-Based Simulation Approach.” *International Journal of Production Research* 52 (17): 4950–66.

Olesen, Jesper. 1992. “Concurrent Development in Manufacturing - Based on Dispositional Mechanisms.” PhD diss., DTU.

Oscarsson, Jan, and MU Moris. 2002. “Documentation of Discrete Event Simulation Models for Manufacturing System Life Cycle Simulation.” In *Proceedings of the Winter Simulation Conference*, edited by E Yücesan, C.-H. Chen, J. L. Snowdon, and J. M. Charnes, 2:1073–78. San Diego, California, USA: IEEE.

Perera, T, and K Liyanage. 2000. “Methodology for Rapid Identification and Collection of Input Data in the Simulation of Manufacturing Systems.” *Simulation Practice and Theory* 7 (7): 645–56.

Ravn, Poul Martin, Tómas Vignir Guðlaugsson, and Niels Henrik Mortensen. 2014. “Visual Modelling of Pilot Production to Support Decision Making in Production Development.” In *Proceedings of the 13th International Design Conference DESIGN 2014*, edited by D. Marjanović, M. Štorga, N. Pavković, and N. Bojčetić, 1179–88. Dubrovnik, Croatia: Design Society.

Rother, Mike, and John Shook. 1999. *Learning to See - Value Stream Mapping to Create Value and Eliminate Muda*. 1.2 ed. Brookline, MA: The Lean Enterprise Institute, Inc.

Russell, Roberta S., and Bernard W. Taylor III. 2011. *Operations Management - International Student Version*. 7th ed. Hoboken, NJ: John Wiley & sons (Asia) Pte Ltd.

Sanchez, Ron. 1995. “Strategic Flexibility in Product Competition.” *Strategic Management Journal* 16 (S1): 135–59.

Sethi, Andrea Krasa, and Suresh Pal Sethi. 1990. “Flexibility in Manufacturing: A Survey.” *International Journal of Flexible Manufacturing Systems* 2 (4): 289–328.

Silla, Harry. 2003. *Chemical Process Engineering - Design and Economics*. Vol. 20030862. Chemical Industries. New York, NY: Marcel Dekker.

Skinner, Wickham. 1985. *Manufacturing - The Formidable Competitive Weapon*. New York: Wiley.

Suh, Nam P. 1995. “Design and Operation of Large Systems.” *Journal of Manufacturing Systems* 14 (3): 203–13.

Suh, Nam P., David S. Cochran, and Paulo C. Lima. 1998. “Manufacturing System Design.” *CIRP Annals - Manufacturing Technology* 47: 627–39.

Taguchi, Genichi, Subir Chowdhury, and Yuin Wu. 2004. “Robust Technology Development.” In *Taguchi’s Quality Engineering Handbook*, 352–76. Hoboken, NJ, USA: John Wiley & Sons, Inc.

Ulrich, Karl T. 1995. “The Role of Product Architecture in the Manufacturing Firm.” *Research Policy* 24 (3): 419–40.

Walsh, Steven T. 2004. “Roadmapping a Disruptive Technology: A Case Study The Emerging Microsystems and Top-down Nanosystems Industry.” *Technological Forecasting and Social Change* 71 (1-2): 161–85.

Yang, B., and N. Burns. 2003. “Implications of Postponement for the Supply Chain.” *International Journal of Production Research* 41 (9): 2075–90.

Zelenović, DM. 1982. “Flexibility - a Condition for Effective Production Systems.” *International Journal of Production Research* 20 (3): 319–37.

Zhang, Linda Lianfeng. 2007. “Process Platform-Based Production Configuration for Mass Customization.” PhD diss., Nanyang Technological University.

Zhang, Linda Lianfeng, and Jianxin Roger Jiao. 2013. “A Graph Rewriting System for Process Platform Planning.” *Decision Support Systems* 54 (2). Elsevier B.V.: 1174–91.

APPENDIX H

About the author

I hold an MSc in Design and Innovation Engineering from DTU. My professional interests lie within product platforms, product development, technology management, and innovation management. Prior to the university studies, I was a fire-fighter and EMT at the Fire and Emergency Services, US Naval Air Station Keflavik.

I am fluent in spoken and written Icelandic—my native language—Danish, and English.

My personal interests include spending time with the family, experiencing new places, participating in various forms of outdoor activities and sports, and playing computer games.

Contact

The most up to date contact information can be found in the following online profiles:

LinkedIn profile	https://dk.linkedin.com/pub/tomas-vignir-gudlaugsson/9/b02/1a4
ResearchGate profile	https://www.researchgate.net/profile/Tomas_Gudlaugsson

✦ *In case you are following directions—this is where you stop* ✦

DTU Mechanical Engineering
Section of Engineering Design and Product Development
Technical University of Denmark

Produktionstorvet, Bld. 426
DK-2800 Kgs. Lyngby
Denmark
Phone (+45) 4525 6263
Fax (+45) 4593 1577
www.mek.dtu.dk
ISBN: 978-87-7475-437-4

DCAMM
Danish Center for Applied Mathematics and Mechanics

Nils Koppels Allé, Bld. 404
DK-2800 Kgs. Lyngby
Denmark
Phone (+45) 4525 4250
Fax (+45) 4593 1475
www.dcamm.dk
ISSN: 0903-1685